Climate Change Scenarios for the United Kingdom

Scientific Report

UK Climate Impacts Programme

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Scientific Report

This report was prepared by:

Mike Hulme, Climatic Research Unit, University of East Anglia, and
Geoff Jenkins, Hadley Centre for Climate Prediction and Research, The Met.Office

Contributors: Elaine Barrow[1], Louise Bohn[1], Chris Durman[2], Matthew Eagles[2], Jonathan Gregory[2], Jason Lowe[2], Ruth McDonald[2], John Mitchell[2], Mark New[1], Tim Osborn[1] and David Viner[1]

[1]Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ
[2]Hadley Centre for Climate Prediction and Research, Met. Office, Bracknell RG12 2SY

See the inside back cover for information about UKCIP
and about ordering the CD-ROM that accompanies the scenarios.

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Preface

This Report describes how the climate of the UK has changed in the recent past and presents our understanding of how it may change through the next century in response to the build-up in atmospheric greenhouse gases. The predictions are based on the best information available in 1998. The scenarios of greenhouse gas emissions and concentrations are based on the work of the Intergovernmental Panel on Climate Change and the scenarios of climate change which may follow are based on climate modelling experiments performed by the Hadley Centre.

The purpose of producing this Report is to enable assessments to be made of the possible impacts of climate change in the UK. When and where will damaging effects occur - or what opportunities may be presented that could be exploited? Specifically, the Report was commissioned as an essential first step for the UK Climate Change Impacts Programme. This Programme exists to help stakeholders in the public and private sectors assess their vulnerability to climate change, recognising that some effects are felt indirectly so that an integrated approach is required. The scenarios defined here are those that UKCIP recommend be used in such integrated studies.

There is, of course, large uncertainty about how the climate will change globally, and even more so at the scale of the UK. This issue is addressed by presenting four possible climate futures for the UK as a whole. Additional detail that is often required to assess climate change impacts is provided for the 'medium-high' scenario, including possible changes in climate at regional scales. At all stages, the authors make clear the degree of confidence that exists in the predictions and also the natural variability that is inherent in he climate system.

Overall, the Report represents a balanced account of the best information currently available on the future climate of the UK. The future is uncertain, but what is most unlikely is that the climate will stay as it is. Given that change will occur, we need to be prepared. This Report alerts us to the future we and our children may face.

Melvin Cannell
Co-chair, UKCIP Science Advisory Panel
Institute of Terrestrial Ecology, Edinburgh
August 1998

Executive Summary

- This Report presents a set of national-level climate change scenarios for the UK, based on our understanding of climate change as of 1998. These scenarios have been commissioned and funded by the Department of Environment, Transport and the Regions for the UK Climate Impacts Programme (UKCIP). We draw upon the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and also upon the series of climate modelling experiments performed by the Hadley Centre with their HadCM2 model over the period 1995 to 1997.

- Climate is changing globally and over the UK. Globally, surface climate is warming at the rate of about 0.15°C per decade and has been doing so since the 1970s. The world is about 0.6°C warmer than a hundred years ago. The three warmest years globally have been - in decreasing order - 1997, 1995 and 1990. UK climate is also warming. The 1990s have so far been about 0.5°C warmer than the 1961-90 average and four of the five warmest years in the 340-year Central England Temperature series have occurred since 1988.

- We describe four possible climate futures for the UK. These are called the UKCIP98 climate scenarios and are labelled as: Low, Medium-low, Medium-high and High. These scenarios span a range of emissions scenarios and different climate sensitivities. For all them, the patterns of climate change over the UK are derived from the HadCM2 series of experiments.

- For these four scenarios, atmospheric carbon dioxide concentrations by the 2080s are between 49 and 109 per cent higher than the average 1961-90 level of 334 ppmv; concentrations by 1997 are already about 9 per cent higher. The rate of global warming over the next century ranges from 0.16°C per decade to 0.35°C per decade. Global-mean sea-level rises in all four scenarios, the rate of increase ranging from 2.4 cm per decade to 10 cm per decade.

- The rise in annual-mean temperature over the UK is slightly smaller than for the global average, with a pattern of larger increases in the southeast of the country than in the northwest. Thus by the 2080s, annual temperatures over southeast England are between 1.5° and 3.2°C warmer than the 1961-90 average, but over Scotland only 1.2° to 2.6°C warmer. The warming is generally slightly more rapid in winter than in summer and greater during night-time than day-time. The year-to-year variability of temperature increases in summer, but decreases in winter.

- Changes in mean annual precipitation are quite modest. By the 2080s, annual precipitation increases by between 0 and 10 per cent over England and Wales and between 5 and 20 per cent over Scotland. There are large seasonal differences however: winters and autumns become wetter over the whole UK, by up to 20 per cent for some scenarios. Spring, and especially summer, experiences a contrast between the southeast of the country which gets drier and the northwest which gets wetter. Reductions in summer precipitation over large parts of England reach 10 to 20 per cent by the 2080s. The year-to-year variability in precipitation increases almost everywhere even in seasons and regions when mean precipitation amounts fall.

- Other surface climate variables also change. Diurnal temperature range tends to decrease slightly and while vapour pressure increases, relative humidity remains quite stable or declines slightly. Changes in cloud cover and radiation are inversely related and the patterns generally match those of precipitation. Mean wind speeds change little with the exception of autumn which sees an increase in windiness. Potential evapotranspiration increases in all seasons, by the greatest relative amount in autumn and by the smallest in spring. By the 2080s, summer potential evapotranspiration over southern England is 10 to 20 per cent higher than at present.

- Changes in mean climate will also be accompanied by changes in the frequency of extreme events. Intense daily precipitation events become more frequent, especially in winter, but there is little change in the return periods for daily-mean wind extremes. Changes in storminess are also quite modest, although summer gales become a little more frequent as do very severe winter gales. These modelled changes in wind regimes in the UK are not very robust and experiments with different climate models yield different results.

- The natural variability of UK climate is large, especially for variables such as precipitation and wind speed. This makes it difficult to attach high levels of significance to all of the changes in these variables that result from anthropogenic forcing. Analysis of natural climate variability on 30-year time-scales shows that mean winter and summer precipitation varies by as much as ±10 per cent without any human forcing of the climate system. Mean seasonal UK temperatures vary naturally on these time-scales by only about ±0.5°C, a much smaller range relative to the scenario changes described here.

- The change in mean sea-level around the UK coast closely follows that at a global-scale and leads to large reductions in return periods for certain high tide-levels around parts of the UK coast. Natural vertical land movements must also be considered, however, and these partly offset climate-induced sea-level rise over northern UK and exacerbate the sea-level rise over southern UK. For example, sea-level rise by the 2050s under the Medium-high scenario is 41cm in East Anglia, but only 21cm in the west of Scotland.

- The UKCIP98 scenarios are presented at the spatial resolution of the HadCM2 model. Climate change interpolated from this spatial scale - just four gridboxes for the UK land area - may be added to high resolution observed climatologies for use in impacts work, but such an approach adds no intelligent spatial detail to the actual climate changes. The application of downscaling methods - based either on existing large-scale:small-scale climate relationships or on results from regional climate models - would be necessary for certain impact applications where local climate detail is important. All downscaling methods still rely, however, on the large-scale climate changes generated by the global climate model. Extra precision in downscaled scenarios should not be confused with extra accuracy.

- We cannot attach specific probabilities to the four UKCIP98 scenarios. In one sense the Medium-high and Medium-low scenarios may be seen as being equally likely and the Low and High scenarios may be seen as capturing part of the tails of the distribution of possible climate outcomes for the UK. There may also be more rapid changes in UK climate than are captured by the scenarios shown here, although again these risks are hard to quantify.

Chapter 1: An Introduction to Climate Change Scenarios

1.1 The UKCIP Climate Scenario Report

This Report for the UK Climate Impacts Programme (UKCIP) describes how the climate of the United Kingdom may change during the next 100 years. In this description, we take into account levels of natural climate variability, as well as a range of future greenhouse gas emissions scenarios and different assumed sensitivities of the climate system to these emissions. The resulting climate scenarios are referred to as the UKCIP98 scenarios and follow from earlier studies that were published in 1991 and 1996 by the Climate Change Impacts Review Group of the, then, Department of the Environment. These earlier CCIRG91 and CCIRG96 climate scenarios have been widely used in impacts assessments in the UK. The scenarios described here replace these earlier efforts. The salient differences between the CCIRG scenarios and the new UKCIP98 scenarios are summarised in Appendix 1 of this report.

1.2 Why Do We Need Climate Change Scenarios?

Climate is changing. The industrial economy through its reliance on carbon-intensive energy continues to alter the radiative properties of the Earth's atmosphere as it has done for many decades now. By steadily increasing our emissions of carbon dioxide and other greenhouse gases, we have increased in less than two hundred years the collective atmospheric concentrations of these radiatively active gases by some fifty per cent relative to pre-industrial levels. The climatic consequences of this change to the planetary atmosphere are beginning to emerge and there is increasing statistical and model-based evidence that a human influence on global climate has been detected. Given the inertia in our energy systems and the long memory exhibited by the climate system, this human-induced climate change will become increasingly important relative to natural climate variability during the century to come.

Climate also varies naturally. Developments in climate system science are making us increasingly aware of the variety of time and space-scales at which climates vary. The causes of natural climate variations include volcanic eruptions and changes in solar variability, as well as natural oscillations within the climate system, such as the North Atlantic Oscillation and El Niño. On longer time-scales changes in the thermohaline circulation of the world's oceans and the orbital characteristics of the Earth are known to have had profound impacts on global climate.

It is for these two reasons - human-induced climate change and an improved understanding of natural climate variability - that we no longer have confidence that the climatic statistics of the recent past will provide us with an adequate description of the climate of the future. No longer is a thirty-year sequence of past weather data - the conventional period used to describe climate established earlier this century by the World Meteorological Organisation - sufficient to define the probabilities of certain weather extremes occurring in the future. As we move into the next millennium therefore, we are becoming increasingly aware of the need to predict as accurately as we can not only the seasonal climate anomalies to be experienced next year, but also the broad sweep of climate change to be encountered over the decades to come. Predicting the weather for next week is no longer sufficient to inform the choices our commercial and governmental institutions need to make.

The major source of greenhouse gas emissions is from the combustion of fossil fuels. Future emissions levels depend on whether carbon fuels continue to dominate our energy economy.

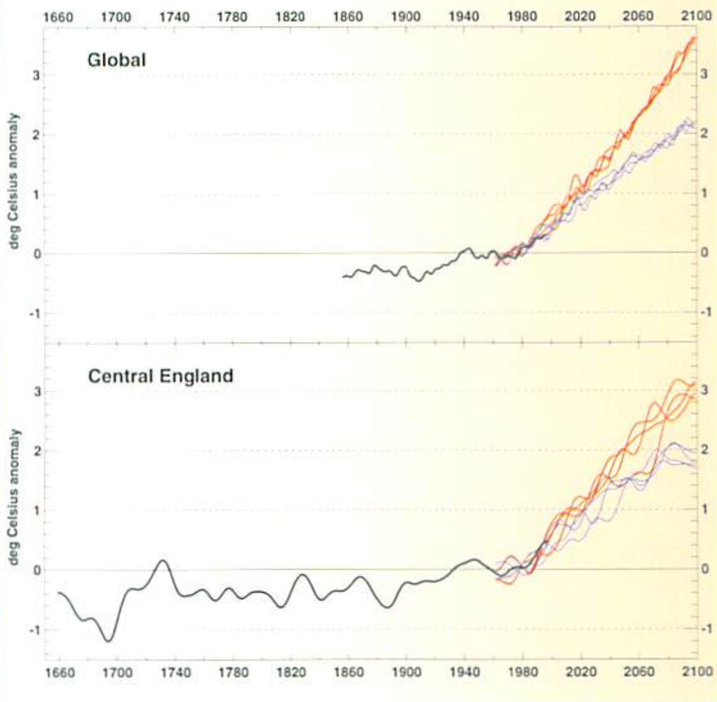

Figure 1: Annual-mean temperature trends for the world and for Central England.

Top Panel: Observed global-mean temperature anomalies from 1856 to 1997 with respect to the 1961-90 mean. Also shown is a range of future global-mean temperature simulations made using the HadCM2 climate model. One cluster of curves results from a high greenhouse gas emissions scenario and one cluster of curves from a low emissions scenario. The curves are smoothed to emphasise 10-year time-scale variability.

Bottom panel: Central England mean annual temperature anomalies from 1659 to 1997 with respect to the 1961-90 mean. Also shown is a range of future central England temperature simulations made using the HadCM2 climate model. One cluster of curves results from a high emissions scenario and one cluster of curves from a low emissions scenario. The curves are smoothed to emphasise 30-year time-scale variability.

Past and possible future changes in climate are summarised in Figure 1. This shows, for the world and for the UK, the historic record of measured surface air temperature changes since 1856 and 1659 respectively. In both series variations in temperature occur from year-to-year and from decade-to-decade for reasons that are probably natural in origin. Both series also show, however, a warming tendency in recent decades, a warming that is unlikely to be solely the result of natural climate variability. Added to these historic curves are a series of simulations of future temperature change for these two domains. These simulations assume two different rates of expansion of the global fossil fuel economy - a high emissions scenario and a low emissions scenario - with in each case no international regulation of greenhouse gas emissions. For each of these two scenarios, and whether for the world or for the UK, natural climate variations alter slightly the detail of the warming - hence the cluster of curves - but the overall magnitude of the change is controlled by the emissions of greenhouse gases. The message is clear: the warming trend that we already see in the observed data will continue into the next century and will probably accelerate.

1.3 What are Climate Change Scenarios?

Climate change scenarios present coherent, systematic and internally-consistent descriptions of changing climates. These scenarios will typically be used as an input into climate change vulnerability, impact or adaptation assessments. Climate change scenarios are most commonly - although not always - constructed using results from Global Climate Model (GCM) experiments. The UKCIP98 scenarios rely largely on one set of GCM experiments completed by the Hadley Centre during 1995 and 1996. These experiments were undertaken using a coupled ocean-atmosphere GCM called HadCM2. This model has been extensively analysed and validated and represents one of the leading global climate models in the world. A brief description of the model and the experiments used in this report is provided in Appendix 2. A new version of the model - HadCM3 - has recently been constructed and a new set of experiments will be completed during 1998 and 1999. Subsequent scenarios for the UKCIP will use results from HadCM3 and later models, but these will not be available until 1999 or later.

1.4 How are Scenarios used in Climate Change Impact Assessment?

Climate change scenarios are used in many different ways by many different individuals or organisations. Some require only a semi-quantitative description of future climate, perhaps as part of a scoping study. Others may need explicit quantification of a range of future climates, perhaps with explicit probabilities attached, as part of a risk assessment exercise. Others still may require information for very specific geographical areas. There are also a range of time horizons considered relevant depending on the type of decision to be made. Water companies may be concerned with operating conditions over the near-term (10-20 years), while coastal engineers or forestry investment decisions may need to consider longer-term horizons. Some examples of these different needs are provided in Table 1. No single set of scenarios can satisfy all of these needs; the national UKCIP98 scenarios described in this Report nevertheless provide a common starting point for all such climate scenario applications.

1.5 Why Climate Change Scenarios and Not Climate Change Predictions?

The main modelling uncertainties in future climate change predictions stem from different values of the climate sensitivity[1] and from the contrasting behaviour of different climate models in their simulation of regional climate change. These latter differences are largely a function of the different schemes employed to represent important processes in the atmosphere and ocean (known as parameterisations) and the relatively coarse resolutions of the models. In HadCM2, for example, the UK land area is represented by just four gridboxes, making it impossible to differentiate between the climate, of say, the Lake District and Merseyside. Predictions are further confounded by the difficulty of disentangling climate change resulting from human modification of the global atmosphere from natural climate variability, as discussed above.

Another important uncertainty in describing future climate, however, is unrelated to the difficulties of climate modelling and stems from the unknown world future. How will global greenhouse gas emissions change in the future? Will we continue to be dominated by a carbon-intensity energy system? What environmental regulation may be introduced to control such emissions? Different answers to these questions can lead to a wide range of possible emissions scenarios. Since all GCM climate change experiments need to choose an emissions scenario, different choices can

Stakeholder	***Decision***	***Scenario requirements***
Countryside managers	*Scoping study of potential sensitivity to climate change*	*Guided sensitivity analysis using a range of historical climatic variations and how they might change given the range of GCM experiments*
Local authority	*Land use planning to assess vulnerability across several sectors*	*National or regional broad-scale scenarios showing a wide range of risk*
Insurance company	*Calculating risk and setting of premiums*	*Nationwide but geographical explicit scenarios, and showing the likelihood of changes in extreme events*
Water supply resource managers	*Whether to begin planning for a new regional reservoir*	*Regional, downscaled scenarios in the context of an explicit probability assessment*

Table 1: Some examples of stakeholder uses for climate change scenarios.

1 The climate sensitivity is defined as the change in global-mean temperature that would be ultimately reached following a doubling of carbon dioxide concentration in the atmosphere (e.g. from 275ppmv to 550ppmv). The Intergovernmental Panel on Climate Change (IPCC) have always reported the likely range for this quantity to be between 1.5° and 4.5°C, with a most likely estimate of 2.5°C.

lead to quite different climate outcomes. We showed the results of two such choices in Figure 1. For all of these reasons we prefer to talk about future climate change scenarios rather than future climate predictions. Predictions, in the sense of being able to attach formal probabilities to the outcomes of specific model experiments, are not yet possible.

1.6 The Selection of Emissions Scenarios

There are clearly a large number of possible alternative world futures to envisage, each of which will have a particular greenhouse gas emissions profile. Seeking the minimum number of scenarios to provide an adequate basis for climate modelling and informing policymakers of the choices open to them is a good principle to apply when choosing emissions scenarios. Scenarios should not be construed as being desirable or undesirable in their own right and are built as descriptions of possible, rather than preferred, developments. There can be no objective assessment of the probability of these emissions scenarios, although some will appear to different individuals to be more likely than others. A detailed discussion of different emissions scenarios is beyond the scope of this Report, although we note that two sets of global emissions scenarios are of potential relevance: the IS92 and SRES98 emissions scenarios. These are discussed in Appendix 3 and the IS92 emissions scenarios are used later in the report when we explore this aspect of uncertainty in climate change scenarios.

1.7 The UKCIP Approach

Given the above difficulties in making firm predictions about future climate, how do we proceed? Do we try and make the 'best' judgement or most likely estimate of future emissions, employ the 'best' model we can find, and then create the 'best' estimate of future climate change? This is the sort of approach that leads to a 'best guess' or 'business-as-usual' climate scenario. Alternatively do we consider a wide range of emissions scenarios and climate modelling uncertainties to try and capture a wide range of possible climate outcomes for a region like the UK? In this case we have to judge where the important extremes in the range of possibilities lie and we have to keep the number of resulting climate scenarios to a manageable minimum. The UKCIP approach is to present four alternative scenarios of climate change for the UK spanning a reasonable range of possible future climates. These scenarios are labelled **Low, Medium-low, Medium-high** and **High,** the labels referring to their respective global warming rates. Of course, impact assessments may wish to consider additional scenarios, such as the full IPCC suite (see Chapter 7) or as new GCM experiments become available (see Chapter 8). In the analysis presented in this Report, we work from the global-scale to the scale of the UK, and then from seasonal changes in mean climate for a range of scenarios to a more detailed set of variables for one of these scenarios - the **Medium-high.** We list the key assumptions we have made in Box A.

1.8 The Outline of the Report

At the global-scale we explore a range of possible climate and sea-level futures (Chapter 3), this range then providing the context within which we look at what global climate change may mean for the UK. For mean seasonal temperature and precipitation we present this range of scenario outcomes for the UK (Chapter 4), thereby ensuring that the user is fully aware of the range of possible future UK climates. We then develop one of these scenario outcomes (what we call the **Medium-high** scenario) into a fuller and more detailed description of future UK climate, examining changes in variables other than temperature and precipitation, changes in interannual and inter-daily climate variability, and changes in the occurrence of extreme events (Chapter 5). In Chapter 6 we discuss the issue of downscaling, namely, how we can move from broad, national-scale descriptions of future climate to more detailed local descriptions of climate change. The **Medium-high** scenario is then placed in a wider context of possible future climates by exploring in Chapter 7 these changes in relation to natural climate variability and in relation to results from other leading Global Climate Models. We also mention here the possibility of rapid, non-linear changes in climate affecting the UK. We conclude in Chapter 8 with a summary of the uncertainties in the UKCIP98 scenarios and a discussion of future developments in climate scenario construction for the UK. All of this scenario material is prefaced, however, with a brief overview of how UK climate has been changing in the recent past (Chapter 2), an essential context for the interpretation of future climate change.

A number of more technical issues - for example, the construction of baseline present-day climatologies or the technical problems of applying climate change scenarios to impacts assessments - are covered in a series of Appendices. Many of the scenarios contained in this report are supported with sets of maps and data files on an accompanying CD-ROM. This CD-ROM contains an electronic version of the report as well as additional maps and the climate data files. Appendix 9 summarises the contents of the CD-ROM. Appendix 10 contains the Registration Form that needs to be signed in order to acquire the CD, while ordering details are supplied on the inside-back cover.

Box A: The UKCIP98 Climate Scenario Assumptions

- Since no single climate change scenario can adequately capture the range of possible climate futures, we present a range of generalised climate scenarios for the UK.

- This range of generalised scenarios depends on different values for the climate sensitivity, on different future levels of anthropogenic forcing of the climate system, and on different global climate models. We follow the IPCC in determining this range.

- Our scenarios result from future changes in greenhouse gases alone. We do not consider changes in natural forcing factors such as volcanoes or solar variability, nor in the concentration or distribution of sulphate aerosols created by human emissions of sulphur dioxide. The effects of sulphate aerosols on climate are highly uncertain, in addition to which their effects are likely to be transitory and regional. The cooling effects of anthropogenic sulphate aerosols are described later in the report, but are not part of the UKCIP98 scenarios.

- We base our more detailed scenario on the experiments completed using the HadCM2 model. This more detailed scenario assumes a future increase of 1% per annum in greenhouse gas concentrations. This is regarded as a convenient assumption regarding the outcome of future anthropogenic emissions rather than as a best-guess outcome.

- We assume that global climate model results have meaning at the scale of individual gridboxes (typically 300-400 km), but we do not attempt to interpret these results on smaller scales. We simply smooth the model results to match the spatial scale of our observed baseline climatology (10 km). Further UKCIP reports may address the problem of more regionally differentiated scenarios for the UK.

Chapter 2: Recent Trends in UK Climate

The UK possesses some of the longest instrumental climate time series in the world, the longest being the Central England Temperature (CET) series which extends back to 1659. This presents a unique opportunity to examine climate variability in the UK on long time-scales based on observational data. It would be advantageous if we could treat these long time series as describing purely natural climate variability, thus enabling us better to identify what level of human-induced climate change is truly significant. This may not be a correct interpretation, however, since - at least in the most recent century - human forcing of the climate system has been occurring through increased atmospheric concentrations of green-house gases. What we are probably observing, therefore, is a mixture of natural climate variability and human-induced climate change, with the contribution of the latter increasing over time.

The UK possesses some of the longest instrumental climate series in the world. Measurements made at the Radcliffe Observatory in Oxford contribute to the Central England Temperature series. [Photo; Bodleian Library].

It is nevertheless very instructive, before we progress to examine future climate change scenarios, to look back and appreciate the level of climate variability that the UK has been subject to in recent generations. This involves us in examining year-to-year, decade-to-decade and even century-to-century variations in relevant climate indices. It is within this history of past climate that the British environment, economy and society has evolved and to which it has in some measure adapted. Just as future climate change can only be sensibly interpreted against a background of observed climate variability, so too the impacts of future climate change for the UK can only be properly evaluated in the context of environmental and societal adaptation to past climate variability [2]. The first section of this Chapter examines four long climate time series describing different aspects of UK climate. In the second section we present a multi-variate description of the spatial variability of UK climate for the reference period 1961-90 and of the temporal variability of some of these climate variables during the twentieth century.

2.1 Long-term Trends in Temperature

A smoothed version of the Central England Temperature series referred to above has been plotted in Figure 1. We show the annual values of this series in Figure 2, together with a version this time smoothed with a 100-year filter to emphasise the century time-scale trends. From the CET data we emphasise three things. First, there has been a warming of UK climate[3] since the seventeenth century. A linear trend fitted through the time series suggests a warming of about 0.7°C over three hundred years and of about 0.5°C during the twentieth century. Second, this warming has been greater in winter (1.1°C) than in summer (0.2°C). Third, the cluster of warm years at the end of the record means that the last decade - 1988 to 1997 - has been the warmest in the entire series, with four of the five warmest years since 1659 occurring in this short period. The unusual warmth of this recent decade is supported by the sequence of very warm months and seasons shown in Table 2.

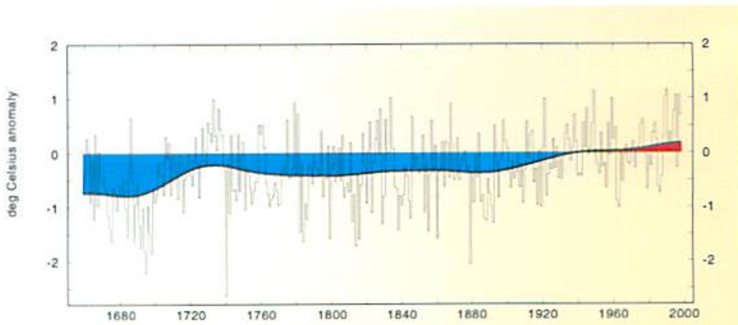

Figure 2: Central England Temperature annual anomalies (degrees Celsius) for the period 1659 to 1997 expressed with respect to the 1961-90 mean (shown by horizontal line). The smoothed curve emphasises century time-scale variability.

[2] In Chapter 7 we examine levels of natural climate variability simulated by a climate model, but for now we use observed data.

[3] Although the Central England Temperature record is based on measurements in the English Midlands, the year-to-year values are highly correlated with temperature variations over most of the UK.

January	1990 +2.7		
February	1990 +3.5	1998 +3.4	
March	1997 +2.7	1990 +2.6	1991 +2.2
April			
May	1992 +2.4		
June			
July	1995 +2.5		
August	1995 +3.4	1997 +3.1	1990 +2.2
September			
October	1995 +2.3	1990 +1.3	
November	1994 +3.6	1997 +2.0	
December			
Winter	1990 +2.2	1998 +2.0	
Spring	1992 +1.7	1997 +1.4	1990 +1.4
Summer	1995 +2.0		
Autumn	1995 +1.2		
Annual	1990 +1.15	1997 +1.06	1995 +1.05

Table 2: Exceptionally warm months, seasons and years during the 1990s as indicated by the Central England Temperature data. To be included, a month, season or year must be one of the ten warmest respective months, seasons or years in the complete 340-year CET series. By chance, and assuming the monthly data were uncorrelated, one would expect only four months, seasons or years to appear in this Table. In fact, 25 exceptionally warm anomalies have occurred during the 1990s. In contrast, only one month - June 1991 - has been exceptionally cold over this period. Anomalies are shown in degrees Celsius with respect to the 1961-90 mean.

The Central England Temperature series can also be used to examine changes in daily temperature extremes, although in this case only since 1772. Figure 3 shows the annual frequencies of 'hot' and 'cold' days in Central England over this period. There has been a marked reduction in the frequency of cold days since the eighteenth century, these frequencies falling from between 15 and 20 per year to around 10 per year over most of the present century. Most of the reduction in cold days occurred before the twentieth century commenced and would therefore appear to be unrelated to human influence on climate. There has been a less perceptible rise in the frequency of hot days, although several recent years (1976, 1983, 1995 and 1997) have recorded among the highest annual frequencies of such days. As with annual temperature, the last decade has seen the highest frequency of such days in the entire series averaging about 7.5 hot days per year, nearly twice the long-term average. The warm year of 1995 recorded 26 hot days in Central England, the highest total in 225 years of measurements.

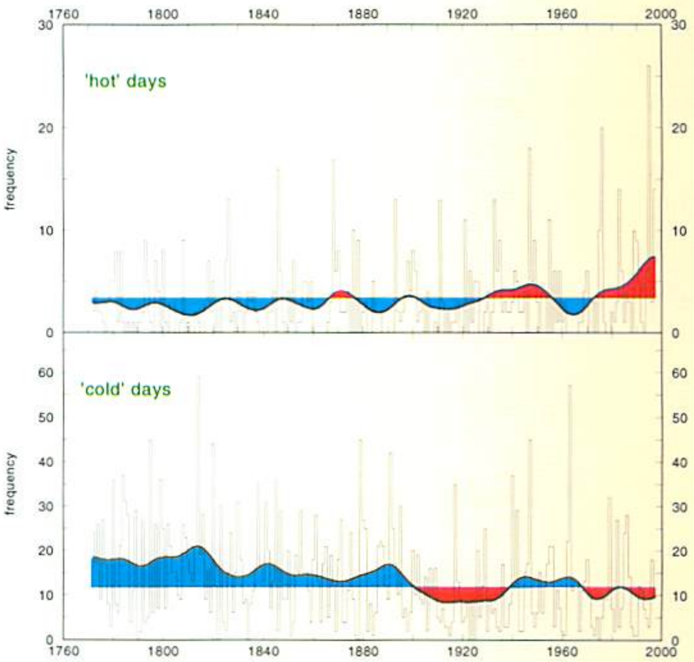

Figure 3: Annual frequency of 'hot' (mean temperature above 20°C) and 'cold' (mean temperature below 0°C) days extracted from the Central England Temperature record for the period 1772 to 1997. The horizontal lines are 1961-90 means and the smooth curves emphasise thirty-year time-scale variability.

2.2 Long-term Trends in Precipitation and Gale Frequencies

There are no comparable long-term trends in annual precipitation, whether over England and Wales or over Scotland (Figure 4). Variations over thirty-year time-scales have, nevertheless, on occasions exceeded ±10 per cent on an annual basis, or over ±20 per cent on a seasonal basis. For example, winter precipitation in Scotland has increased in recent decades, while summer precipitation in England has been falling. These are quite large fluctuations in multi-year precipitation and taking such estimates to be the background level of natural precipitation variability on these time-scales has important implications for how water and other moisture sensitive resources are best managed in the UK.

We also show in Figure 5 an index of gale activity over the UK. This series is not as long as those for temperature and precipitation, but as with precipitation it shows no long-term trend. Gale activity is highly variable from year-to-year, with a minimum of two gales occurring in 1985 and a maximum of 29 gales in 1887. The 1961-90 average is for just over 12 severe gales per year, mostly in the period November to March. The middle decades of this century were rather less prone to severe gales than the early and later decades, whilst the most recent decade - 1988 to 1997 - has recorded the highest frequency of severe gales (15.4 per year) since the series began in 1881.

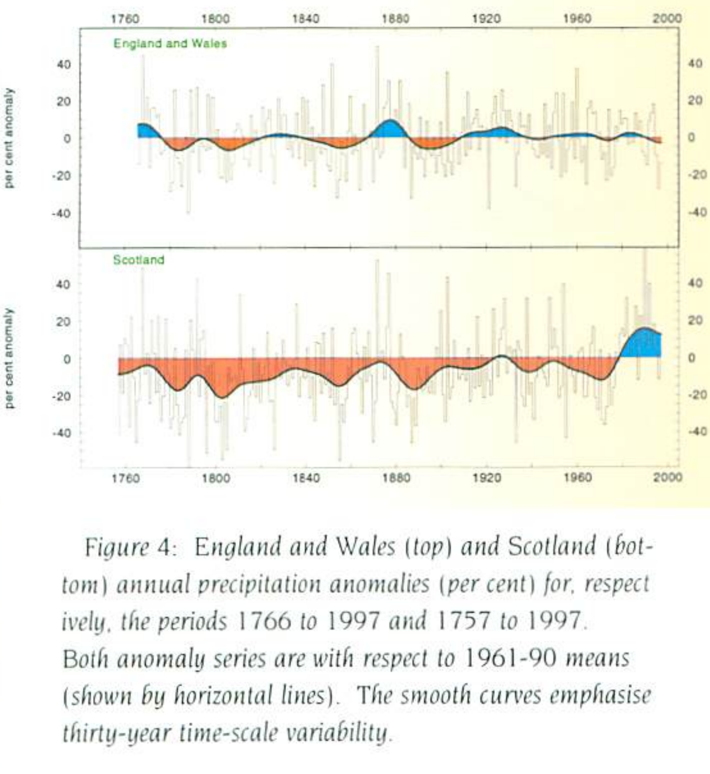

Figure 4: England and Wales (top) and Scotland (bottom) annual precipitation anomalies (per cent) for, respect ively, the periods 1766 to 1997 and 1757 to 1997. Both anomaly series are with respect to 1961-90 means (shown by horizontal lines). The smooth curves emphasise thirty-year time-scale variability.

2.3 Long-term Trends in Sea-level

A final indicator of trends in UK climate relates to sea-level rise. Climate warming is anticipated to lead to a rise in global-mean sea-level, primarily because of thermal expansion of ocean water and land glacier melt. Figure 6 shows long-term series of tide-gauge data for five locations around the UK coastline. All of these series indicate a rise in sea-level, ranging from 0.7mm/yr. at Aberdeen to 2.2mm/yr. at Sheerness. These raw estimates of sea-level change need adjusting, however, to allow for natural rates of coastline emergence and submergence resulting from long-term geological readjustments to the last glaciation. The adjusted net rates of rise resulting only from changes in ocean volume range from 0.3mm/yr. at Newlyn to 1.8mm/yr. at North Shields, evidence of a rising ocean around the UK coastline.

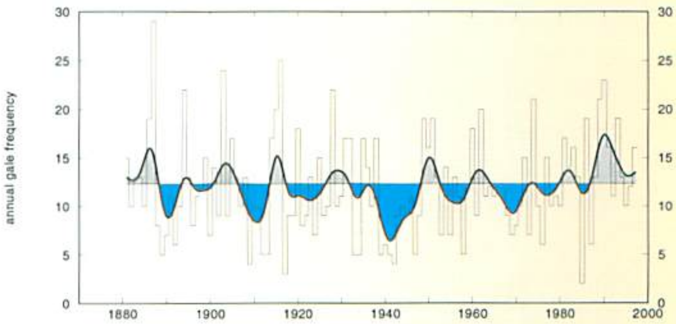

Figure 5: Annual frequency of severe gales affecting the UK for the period 1881 to 1997. The horizontal line shows the average 1961-90 frequency and the smooth curve emphasises decadal time-scale variability.

2.4 1961-90 Mean Climate

To represent the spatial variability of UK climate in the UKCIP98 scenarios, we choose to use mean monthly and seasonal climate fields for the period 1961-90. This period is chosen not because it is necessarily the period most representative of long-term UK climate, but because it is the thirty-year period for which we have best observed data availability in the UK and because it represents a convenient reference period from which we can calculate climate change and its associated impacts. Throughout this report, all climate scenario changes are shown with respect to this average 1961-90 climate.

The 1961-90 climatology we are using has been constructed from between 100 and 10,000 measuring sites, the number depending on which variable is being shown (Appendix 4 describes this climatology in more detail). The climatology exists at a 10 km resolution for the UK land area and has been constructed for the variables shown in Table 3. We include two sample maps - for mean temperature (Figure 7) and precipitation (Figure 8) and for the winter and summer seasons - to illustrate the information contained in this data set. The full set of seasonal and annual maps for all variables, and

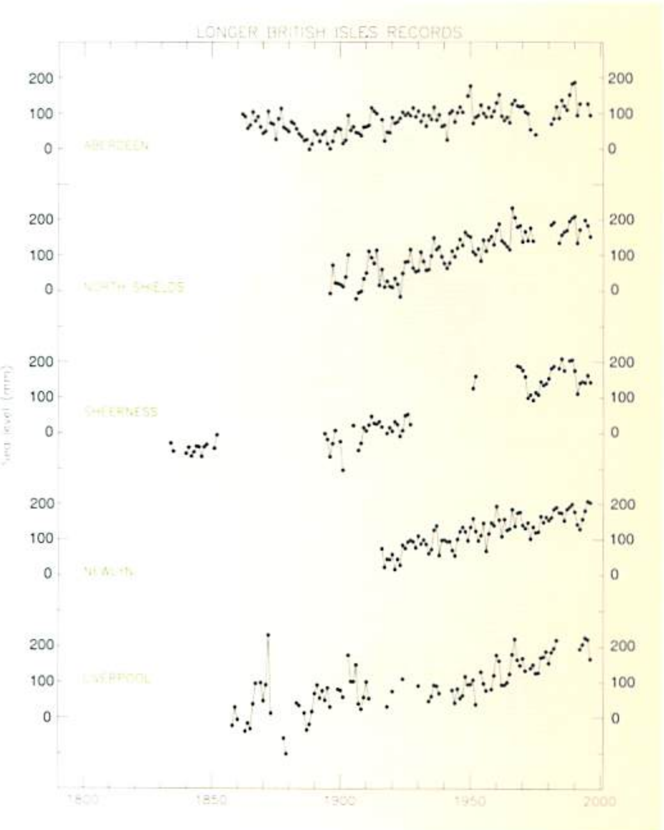

Figure 6: Relative changes in sea-level over the last 100 to 150 years as recorded by tide gauges at five UK locations. Last year of data is 1995 or 1996 and units are mms. Data are unadjusted for crustal movements [source: Woodworth et al., 1998].

the monthly, seasonal and annual data files, are available on the accompanying CD-ROM.

In the plots shown in this section we also indicate how variable thirty-year climates have been during the twentieth century by showing time series from 1900 to 1995 for the four HadCM2 land gridboxes covering the UK (see Chapter 4). These timeseries are extracted from the historic CRU05 global climatology described in Appendix 4. Of the three thirty-year climates shown here - 1901-30, 1931-60 and 1961-90 - the coldest winter climate has been 1961-90 (largely because of the very cold winter of 1962/63) and the warmest summer climate has been 1931-60 (because of the warm summers of the 1920s and 1930s). The mild winters and hot summers of the 1990s do not yet feature in any thirty-year climatology, although when they do the 1971-2000 climatology could well exceed all earlier thirty-year periods for warmth in both winter and summer.

Variable	**Units**	***Number of contributing sites***
Mean temperature	*deg C*	402
Mean minimum temperature	*deg C*	402
Mean maximum temperature	*deg C*	402
Diurnal temperature range	*deg C*	402
Frequency of ground frost days	*Days*	143
Precipitation	*mm*	750$
Frequency of wet days	*Days*	133
Sunshine	*hrs/day*	268
Cloud cover	*Fractional cover*	268*
Global radiation	Wm^{-2}	268*
Vapour pressure	*hPa*	360
Mean wind speed	ms^{-1}	93
Mean maximum daily wind speed	ms^{-1}	121
Interannual temperature variability	*Standard deviation (degC)*	121
Interannual precipitation variability	*Coeff. of variation (%)*	121
Interdaily temperature variability	*Standard deviation (degC)*	121
Interdaily precipitation variability	*Coeff. of variation (%)*	121
Potential evapotranspiration	*mm/day*	*n/a#*

*Table 3: List of surface climate variables contained in the 1961-90 mean monthly 10 km climatology for the UK. The numbers of contributing sites are also shown. Notes: * derived from sunshine hours; # calculated from other variables using the Penman formula; $ number used in the interpolation (over 9,000 sites in the full dataset).*

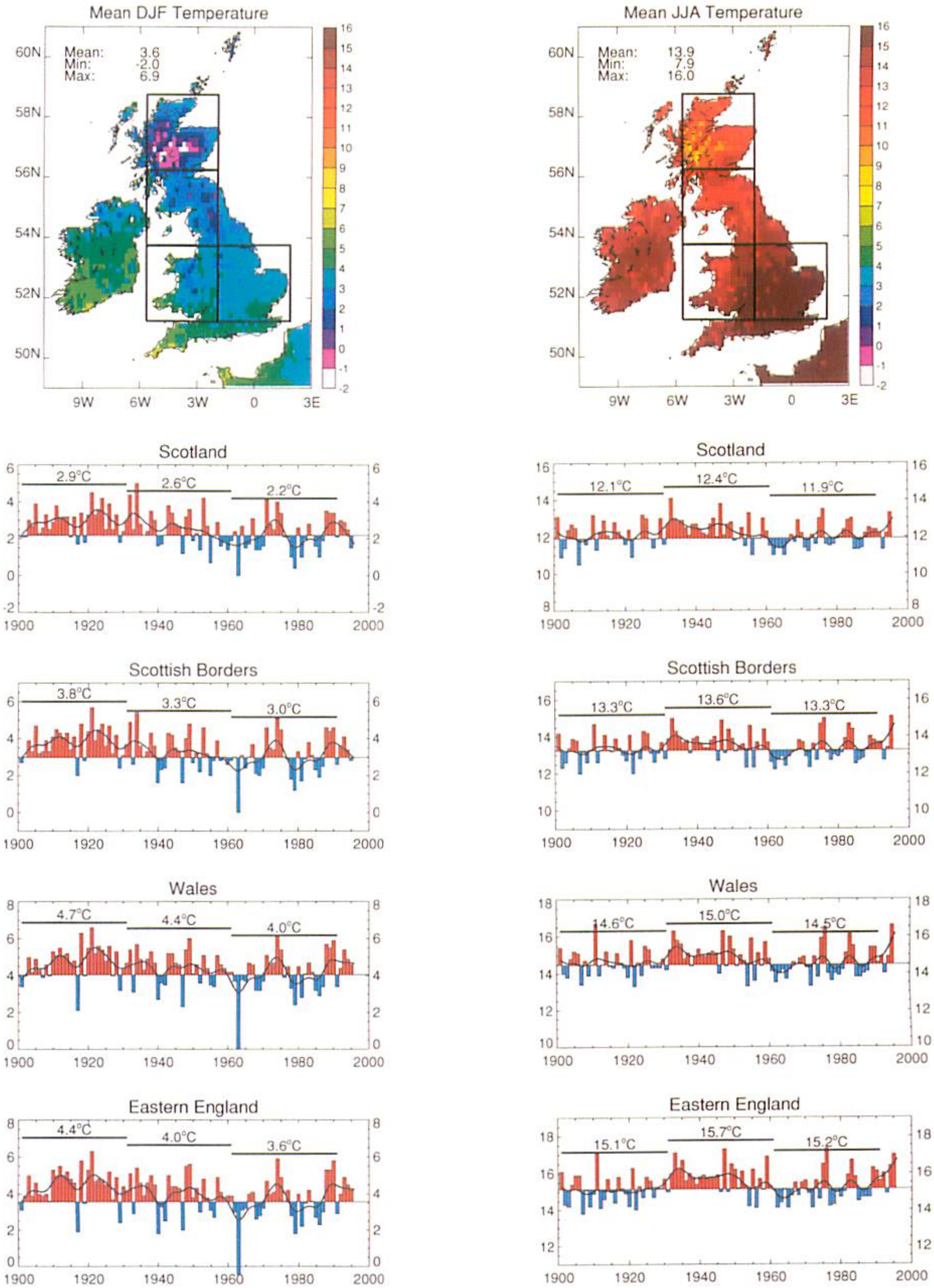

Figure 7: Mean 1961-90 winter (left) and summer (right) temperature over the UK (degrees Celsius). Time series show 1901-1995 variations in seasonal temperature with respect to the 1961-90 average for the four respective HadCM2 land grid-boxes highlighted on the map. The three horizontal lines on the graphs quantify the mean temperature for the periods 1901-30, 1931-60 and 1961-90.

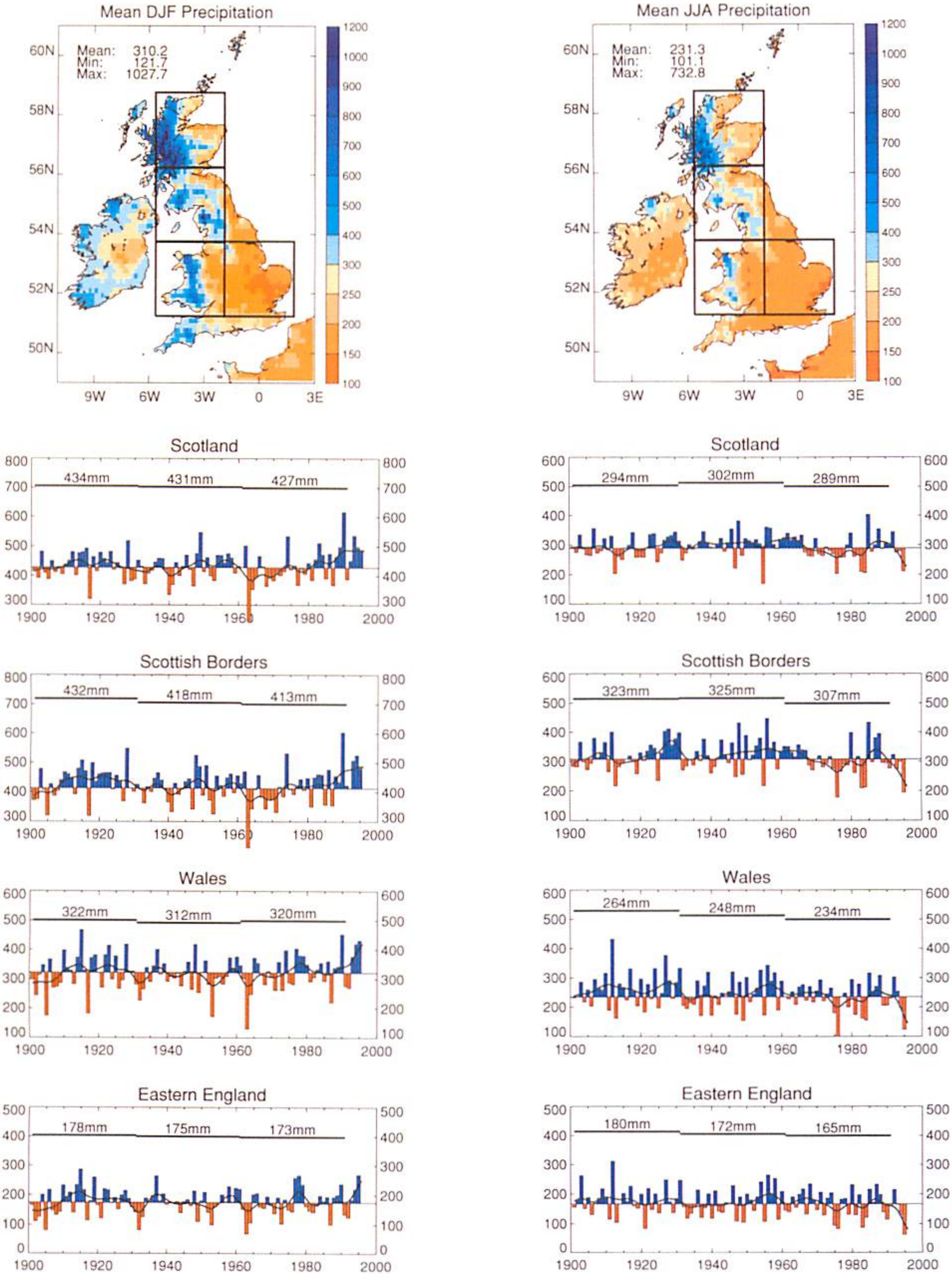

Figure 8: Mean 1961-90 winter (left) and summer (right) precipitation over the UK (mm). Time series show 1901-1995 variations in seasonal precipitation with respect to the 1961-90 average for the four respective HadCM2 land gridboxes highlighted on the map. The three horizontal lines on the graphs quantify the mean precipitation for the periods 1901-30, 1931-60 and 1961-90.

Chapter 3: Future Changes in Global Climate

Starting our description of future climate change at the global scale allows us to explore the relative importance of two factors that affect our estimation of future climate change, namely, how will greenhouse gas emissions change in the future and how will climate respond to this change. The first factor depends upon, *inter alia*, different interpretations of the Kyoto Protocol and the second factor upon which climate model is used. In this Chapter we show the effects of these two factors on global temperature calculations for the next century. For the four UKCIP98 scenarios we also summarise the associated changes in global-mean sea-level and atmospheric carbon dioxide concentrations. In this global-scale analysis we use results from the HadCM2 experiments (these will later provide the results for the UKCIP98 scenarios), results from other Global Climate Model experiments available through the IPCC Data Distribution Centre (see Appendix 5), and results from the simple climate model used by the IPCC in their Second Assessment Report. The use of this latter model allows us to explore a wider range of outcomes than could be studied using GCMs alone. In none of these analyses have we included the modest direct cooling effect of sulphate aerosols. We discuss the reasons for this decision and its significance in Box B.

Box B: The Relevance of Sulphate Aerosol Forcing

Climate can also be affected by a number of other agents in addition to greenhouse gases; important amongst these are small particles (aerosols). These aerosols are suspended in the atmosphere and some types (e.g. sulphate aerosols derived from sulphur dioxide) reflect back solar radiation, hence they have a cooling effect on climate. Although there are no measurements to show how these have changed over the past 150 years, there are estimates of how sulphur dioxide emissions have risen (one of the main precursors for aerosol particles) and projections of such emissions into the future. Two such projections have been used in a sulphur cycle model to calculate the accompanying rise in sulphate aerosol concentrations. When one of these was used, along with greenhouse gas increases, as input to the HadCM2 model, the global temperature rise to 2100 was reduced by between a quarter and a third.

This is a very uncertain calculation, however, due to a number of factors. First, the IPCC emissions scenario on which it was based contains large rises in sulphur dioxide emissions over the next century. More recent estimates of these emissions see only a small rise over the next couple of decades followed by reductions to levels lower than today's by 2100. The inclusion of such a modest sulphur dioxide emissions scenario would actually produce a temperature rise relative to a model experiment that excluded the aerosol effect. Second, more recent sulphur cycle models generate a lower sulphate burden per tonne of sulphur dioxide emissions and the radiative effect of the sulphate particles in more sophisticated radiation models is smaller than previously calculated. Third, in addition to their direct effect, sulphate aerosols can also cool climate by changing the reflectivity and longevity of clouds. These indirect effects are now realised as being as at least as important as the direct effect, but were not included in HadCM2 simulations. Fourth, there are other types of aerosols (e.g. carbon or soot) which may also have increased due to human activity, but which act to warm the atmosphere. Above all, the short lifetime of sulphate particles in the atmosphere means that they should be seen as a temporary masking effect on the underlying warming trend due to greenhouse gases. For all these reasons, HadCM2 simulations of future climate change both greenhouse gases and sulphate aerosols have not been used to develop the UKCIP98 scenarios.

3.1 The Effect of Different Emissions Scenarios

We start by assessing the significance of different greenhouse gas emissions scenarios for the calculation of future global temperature change. Figure 9 shows the warming curves for the six IS92 emissions scenarios published by the IPCC, with all calculations assuming a standard climate sensitivity of 2.5°C. These calculations allow for no natural climate variability, whether internally generated or externally forced, since they were made using a simple climate model. Also shown are the warming rates calculated by the HadCM2 model when forced with 'high' (what we call GGa) and 'low' (GGd) greenhouse gas forcing scenarios. In these GCM simulations, natural climate variability internal to the climate system *is* simulated, but natural external forcing (e.g. solar variability, volcanic emissions) of the system is ignored. The two forcing scenarios used in the HadCM2 experiments are the equivalent of a 1% (GGa) and 0.5% (GGd) per annum increase in equivalent[4] carbon dioxide concentrations. These forcing scenarios are not greatly different from the IS92a and IS92d emissions scenarios, hence the terminology 'a' and 'd'.

Future greenhouse gas emissions will depend on changing land use patterns as well as energy technology and consumption trends.

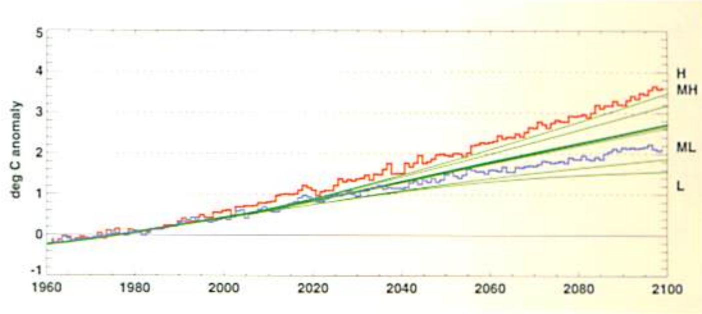

Figure 9: Global-mean temperature anomalies (with respect to 1961-90 mean) from 1960 to 2100 for the HadCM2 *experiments (*GGa *and* GGd *ensemble-means; red and blue histograms) and for the six* IS92 *greenhouse gas emissions scenarios with a climate sensitivity of* 2.5°C *(green curves). The thick green curve is the* IS92a *emissions scenario. No sulphate aerosol effects are included in any of these calculations. The* IS92 *curves are based on* IPCC 1995 *(Kattenberg et al.,* 1996*). The relative warmings by* 2100 *of the four* UKCIP98 *scenarios are shown by the bold letters:* L, ML, MH *and* H.

The HadCM2 GGa warming curve falls just outside the upper end of the range of these temperature calculations made with the simple model. There are two main reasons for this. First, the climate sensitivity in HadCM2 is somewhat higher than the 2.5°C value chosen for the simple model and, second, a 1% per annum forcing increase is slightly greater than that due to the IS92a emissions scenario. The GGd curve falls towards the lower end of this range. Even with a perfect climate model we would still have this level of uncertainty (i.e., a range of warming from about 1.6°C to 3.5°C by 2100) in our calculation of future global climate change. This uncertainty reflects the wide range of the possible global economic, demographic and technological futures that will control future emissions of greenhouse gases.

3.2 The Effect of Different Climate Sensitivities

We next show the effect of changing the value of the climate sensitivity (Figure 10). Here, the warming curves from the HadCM2 GGa and GGd simulations are again shown, but this time alongside the IPCC calculation of global warming assuming the IS92a emissions scenario with three

4 'Equivalent' carbon dioxide concentrations are used in the HadCM2 *experiments because this model cannot handle different greenhouse gas species individually. The concentrations used may therefore represent many different possible combinations of carbon dioxide, methane, nitrous oxide and halocarbon concentrations, but all of which yield the same gross radiative forcing. The new version of the Hadley Centre model (*HadCM3*) is able to treat gas species individually.*

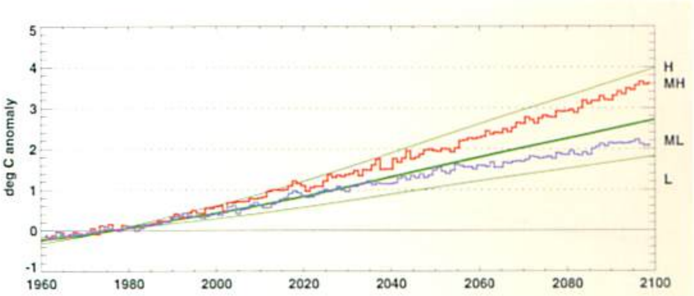

Figure 10: Global-mean temperature anomalies (with respect to 1961-90 mean) from 1960 to 2100 for the HadCM2 experiments (GGa and GGd ensemble-means; red and blue histograms) and for the IS92a greenhouse gas emissions scenario with climate sensitivities of 1.5°C, 2.5°C and 4.5°C (green curves). The thick green curve is for the 2.5°C sensitivity. No sulphate aerosol effects are included in any of these calculations. The IS92 curves are based on IPCC 1995 (Kattenberg et al., 1996). The relative warmings by 2100 of the four UKCIP98 scenarios are shown by the bold letters: L, ML, MH and H.

different values for the climate sensitivity - 1.5°C, 2.5°C and 4.5°C. This range of values for the climate sensitivity is that quoted by the IPCC in their Second Assessment Report, although it should be noted that the more recent coupled ocean-atmosphere model experiments generate a range for this quantity between about 2.5° and 3.5°C. The range of warming due to different climate sensitivities (from 1.8°C to about 4°C in 2100) is slightly larger than that due to the different emissions scenarios of Figure 9.

3.3 The Effect of the Kyoto Protocol

The six emissions scenarios used in Figure 9 result from different visions of the world future, but all of them exclude climate policy interventions. In Figure 11 we consider what effect three different interpretations (we term these K1, K2 and K3) of the recently agreed Kyoto Protocol may have on these calculations[5]. K1 assumes literal adherence to the Protocol by Annex I countries, but no further (post-2012) emissions controls. K2 assumes that Annex I countries continue to reduce greenhouse gas emissions at the rate of 1% per year through to 2100[6]. K3 assumes Annex I countries follow the K2 case, but that after 2020 all other countries also begin to reduce greenhouse gas emissions from 2020 levels by 1% per annum through to 2100. The reduction in global warming by 2100 under the K1 and K2 scenarios is modest (at most 0.2° or 0.3°C), whereas the K3 scenario reduces the 2100 warming by about 0.7°C. For comparison, the HadCM2 GGd warming curve lies somewhere between the K2 and K3 scenarios.

3.4 The Effect of Different Global Climate Models

Finally, in Figure 12 we compare the HadCM2 GGa and GGd warming curves with those generated by three other coupled ocean-atmosphere GCMs when forced with a 1% per annum increase in equivalent carbon dioxide concentrations. These GCMs are those adopted by the IPCC Data Distribution Centre (see Appendix 5). The range of warming shown here (3.1°C to 5.6°C by 2100) reflects how sensitive estimated global warming is to the choice of climate model. This range is in large part again related to different values of the climate sensitivity, but also reflects differences in model and experimental design.

The extent to which the Kyoto Protocol will be adhered to will depend on many factors, including the uptake of new, renewable energy technologies

5 *In each case, emissions reductions resulting from Kyoto are calculated with respect to the IS92a emissions profile. It would be equally legitimate to repeat this analysis using in turn each of the other five IS92 emissions profiles as the reference case.*

6 *1% per year reduction is approximately the rate such countries are required to adhere to over the period 1998-2012.*

3.5 The UKCIP98 Scenarios

With the above analyses in mind, it is important that we present a range of climate change scenarios for the UK that adequately reflect the uncertainties in future global warming rates summarised in Figures 9 to 12. No single scenario can of course capture these uncertainties. For the UKCIP98 scenarios we choose four of these global warming outcomes and relate the spatial and temporal changes in UK climate to these four different rates of global warming. These four scenarios are explained below and the associated changes in global-mean temperature, sea-level and carbon dioxide concentration are summarised in Table 4 (equivalent numbers for all the other simulations described in this chapter are presented in Appendix 6). The relative positions of the four UKCIP98 scenarios in terms of global warming by 2100 are shown by the respective letters on each of Figures 9 to 12.

These four UKCIP98 scenarios contain global warmings by the period 2010-2039 (i.e., the 2020s)

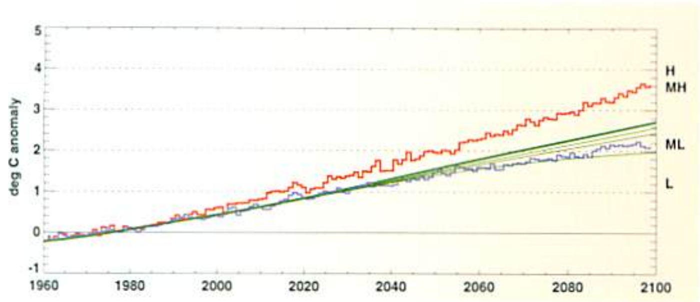

Figure 11: Global-mean temperature anomalies (with respect to 1961-90 mean) from 1960 to 2100 for the HadCM2 *experiments* (GGa *and* GGd *ensemble-means; red and blue histograms), for the* IS92a *greenhouse gas emissions scenario with a climate sensitivity of* 2.5°C *(thick green curve), and for three greenhouse gas emissions scenarios related to three interpretations of the* Kyoto Protocol, K1, K2 *and* K3 *(see text for explanation; thin green curves). No sulphate aerosol effects are included in any of these calculations. The* IS92 *curves are based on* IPCC 1995 (Kattenberg *et al.*, 1996) *and the* Kyoto Protocol *scenarios on* Wigley (1998). *The relative warmings by* 2100 *of the four* UKCIP98 *scenarios are shown by the bold letters:* L, ML, MH *and* H.

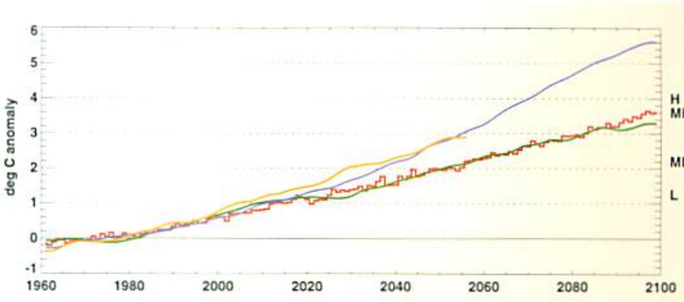

Figure 12: Global-mean temperature anomalies (with respect to 1961-90 mean) from 1960 to 2100 for the HadCM2 *experiment* (GGa *ensemble-mean; red histogram) and for three other coupled* GCM *simulations forced with a* GGa*-type emissions scenario:* CGCM1 *(blue),* ECHAM4 *(green) and* GFDL-R15 *(orange). The* GFDL-R15 *experiment ends in* 2058. *No sulphate aerosol effects are included in any of these calculations. The relative warmings by* 2100 *of the four* UKCIP98 *scenarios are shown by the bold letters:* L, ML, MH *and* H.

> **Low (L):** IS92d *emissions scenario with a low* (1.5°C) *climate sensitivity.*
> **Medium-low (ML):** *the* HadCM2 GGd *forced experiment.*
> **Medium-high (MH):** *the* HadCM2 GGa *forced experiment.*
> **High (H):** IS92a *emissions scenario with a high* (4.5°C) *climate sensitivity.*

that range from about 0.6° to 1.4°C, a decadal rate of warming of between 0.11° and 0.28°C. The observed global-mean surface temperature data for the last two decades reveal that the world has already been warming by about 0.14°C per decade (Table 4)[7]. By the period 2070-2099 (i.e., the 2080s) the scenarios generate a warming range of 1.1°C to 3.5°C, broadly similar to the range resulting from the different emissions scenarios shown in Figure 9. The **Medium-low** and **Medium-high** scenarios yield global warmings by the 2080s of, respectively, 1.9° and 3.1°C and thus provide scenarios that sample the mid-range of the possible global climate change. We present generalised results for the UK from these four scenarios in Chapter 4 and more detailed results for the **Medium-high** scenario in Chapter 5.

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7 *This observed rate of warming is quite consistent with the* UKCIP98 *scenarios, although being calculated over only* 30 *years of data one should be cautious about over-interpreting its significance.*

The global-mean sea-level changes and carbon dioxide concentrations associated with the four UKCIP98 scenarios (Table 4) similarly reflect a range of values that may be used in climate change impacts assessments. Pre-industrial carbon dioxide concentrations (~ 275 ppmv) double by the 2050s under the **Medium-high** scenario and the average 1961-90 concentration (~ 334 ppmv) doubles by the 2080s under this scenario. Changes are more modest for the **Low** and **Medium-low** scenarios, so that even by the 2080s concentrations remain below the pre-industrial doubling level (515 and 498 ppmv respectively). Global-mean sea-level rises throughout each scenario, but the rate of rise varies from about 2 cm per decade for the **Low** scenario to about 9 cm per decade for the **High** scenario.

Future carbon dioxide concentrations in the atmosphere will be strongly influenced by the ability of ecosystems to sequester carbon

1980s	1990s*		2020s			2050s			2080s		
ΔT degC	ΔT degC		ΔT degC	ΔSL cm	CO_2 ppmv	ΔT degC	ΔSL cm	CO_2 ppmv	ΔT degC	ΔSL cm	CO_2 ppmv
0.13	0.28	***Low***	0.57	7	415	0.89	12	467	1.13	18	515
0.13	0.28	***Medium-low***	0.98	8	398	1.52	18	443	1.94	29	498
0.13	0.28	***Medium-high***	1.24	12	447	2.11	25	554	3.11	41	697
0.13	0.28	***High***	1.38	38	434	2.44	67	528	3.47	99	637

Table 4: Global climate change estimates for three future time-slices for the four UKCIP98 scenarios. Changes in global temperature and sea-level are calculated with respect to the 1961-90 mean. The time-slices are thirty-year means centred on the decades shown. No sulphate aerosol effects have been considered. The data for the 1980s and 1990s are observed global-mean temperature changes, again calculated with respect to the 1961-90 mean. The CO_2 concentrations for the ***Low*** *and* ***High*** *scenarios are taken from the IPCC, while for the* ***Medium-low*** *and* ***Medium-high*** *they are estimated from the HadCM2 experiments; the forcing scenarios used in each case are not directly comparable explaining why the global warming rates do not precisely follow the CO_2 concentrations.*

Chapter 4: Future Changes in UK Climate

This chapter presents climate changes for the UK for the four UKCIP98 scenarios defined at the end of Chapter 3. We concentrate primarily on mean temperature and precipitation. Other variables for the **Medium-high** scenario are summarised in Table 7 and a larger set of data files are available on the CD-ROM. The **Low** scenario patterns are derived from the HadCM2 GGd experiment and the **High** scenario patterns from the HadCM2 GGa experiment. In each case, the GCM patterns are scaled[8] by the respective global warming curves to yield magnitudes of change for the UK consistent with these low (1.1°C warming by the 2080s) and high (3.5°C) rates of global warming. The change patterns for the **Medium-low** (1.9°C warming by the 2080s) and **Medium-high** (3.1°C) scenarios are extracted directly from the respective HadCM2 experiments, GGd and GGa. In Chapter 5 we present more detailed results for the UK - more variables and different types of analyses - for the **Medium-high** scenario, drawing upon HadCM2 GGa results.

In all the maps and results shown in this Report and on the CD-ROM, we present climate changes for three future thirty-year periods centred on the 2020s, the 2050s and the 2080s. The climate changes for each of these periods are calculated as the change in thirty-year mean climates with respect to the 1961-90 average. The 2020s are therefore representative of the period 2010-2039, the 2050s of 2040-2069 and the 2080s of 2070-2099. In later chapters we show changes in climate variability within these periods and show the evolution of UK climate throughout the next century. The thirty-year mean changes shown here provide an initial assessment of the respective scenario changes for UK climate.

It is also important to recognise that the changes shown here are those anticipated to result from greenhouse gas forcing of the climate system under the assumptions discussed in Chapters 1 and 3. Natural climate variability (i.e., the noise of the system) will in reality modify these magnitudes and patterns of change, whether this variability is internally generated or whether it results from external factors such as solar variability or volcanic eruptions[9]. Chapter 7 quantifies one component of this natural climate variability and the results shown both in this chapter and in Chapter 5 should be interpreted in this context.

4.1 Changes in Mean Temperature

Figures 13, 14 and 15 show the annual, winter and summer changes in mean temperature for the four UKCIP98 scenarios. In all seasons and for all scenarios there is a northwest to southeast gradient in the magnitude of the climate warming over the UK, the southeast consistently warming by several tenths of a degree Celsius more than the northwest. Warming rates vary from about 0.1°C per decade for the **Low** scenario to about 0.3°C for the **High** scenario. These UK warming rates are very similar to the global-mean warming rates calculated in Chapter 3. Although in general, warming is greater in winter than in summer, this is not always the case. In the **Medium-low** scenario for the 2080s for example, summers warm by 2.4°C over southeast England while winters are only 2.0°C warmer than the 1961-90 average.

A warming climate may make viticulture in Southern Britain a more attractive prospect. (photo: Julie Jones)

8 *The justification for scaling these GCM patterns is discussed in Appendix 7*

9 *By showing the ensemble-mean results from these GCM experiments we have, however, deliberately maximised this greenhouse gas signal with respect to the noise of natural climate variability.*

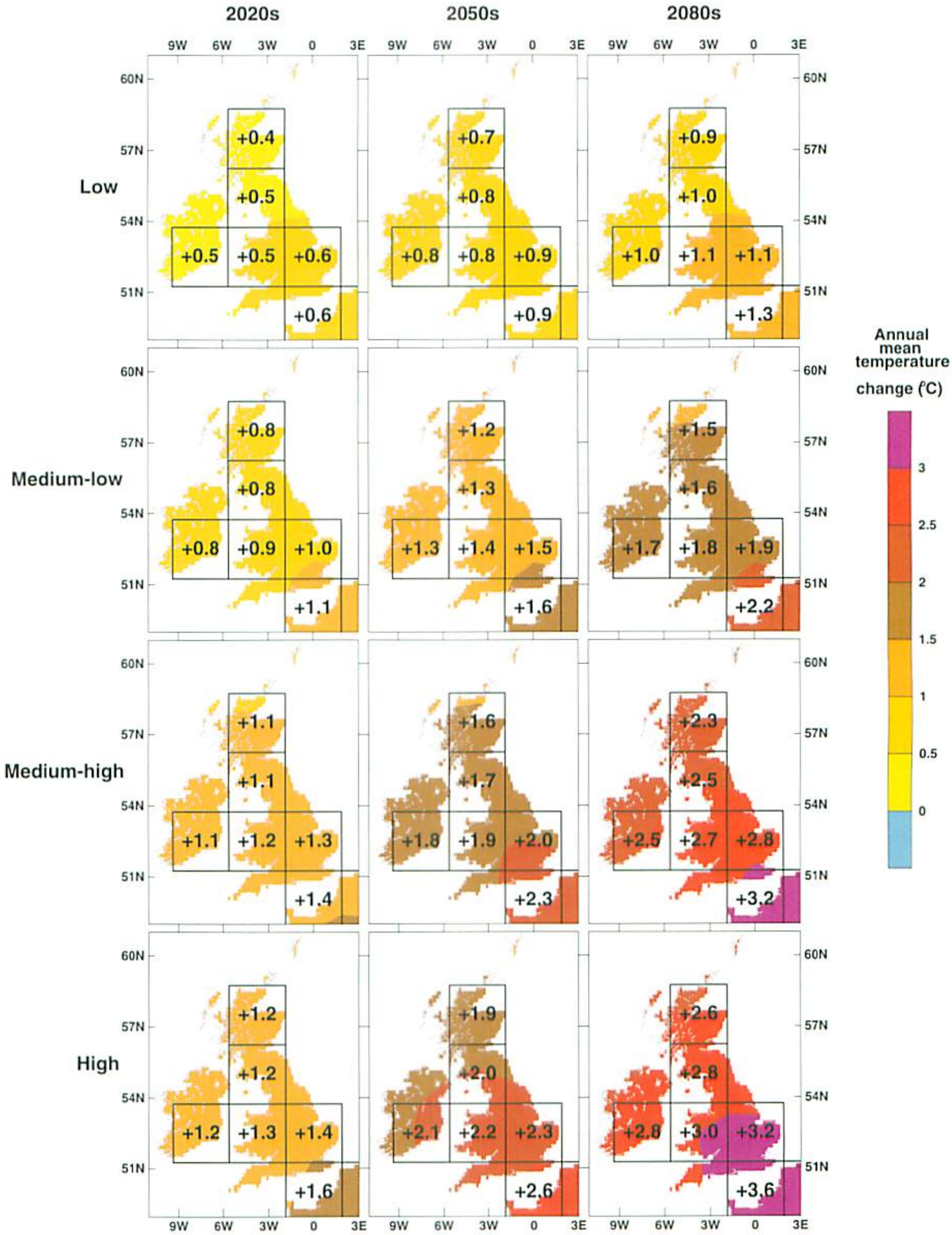


Figure 13: Change in mean annual mean temperature (with respect to the 1961-90 mean) for thirty-year periods centred on the 2020s, 2050s and 2080s and for the four UKCIP98 scenarios. Top: ***Low*** *scenario, changes are scaled from the HadCM2 GGd ensemble-mean. Second row:* ***Medium-low*** *scenario, changes are from the HadCM2 GGd ensemble-mean. Third row:* ***Medium-high*** *scenario, changes are from the HadCM2 GGa ensemble-mean. Bottom:* ***High*** *scenario, changes are scaled from the HadCM2 GGa ensemble-mean. Background fields are interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK.*

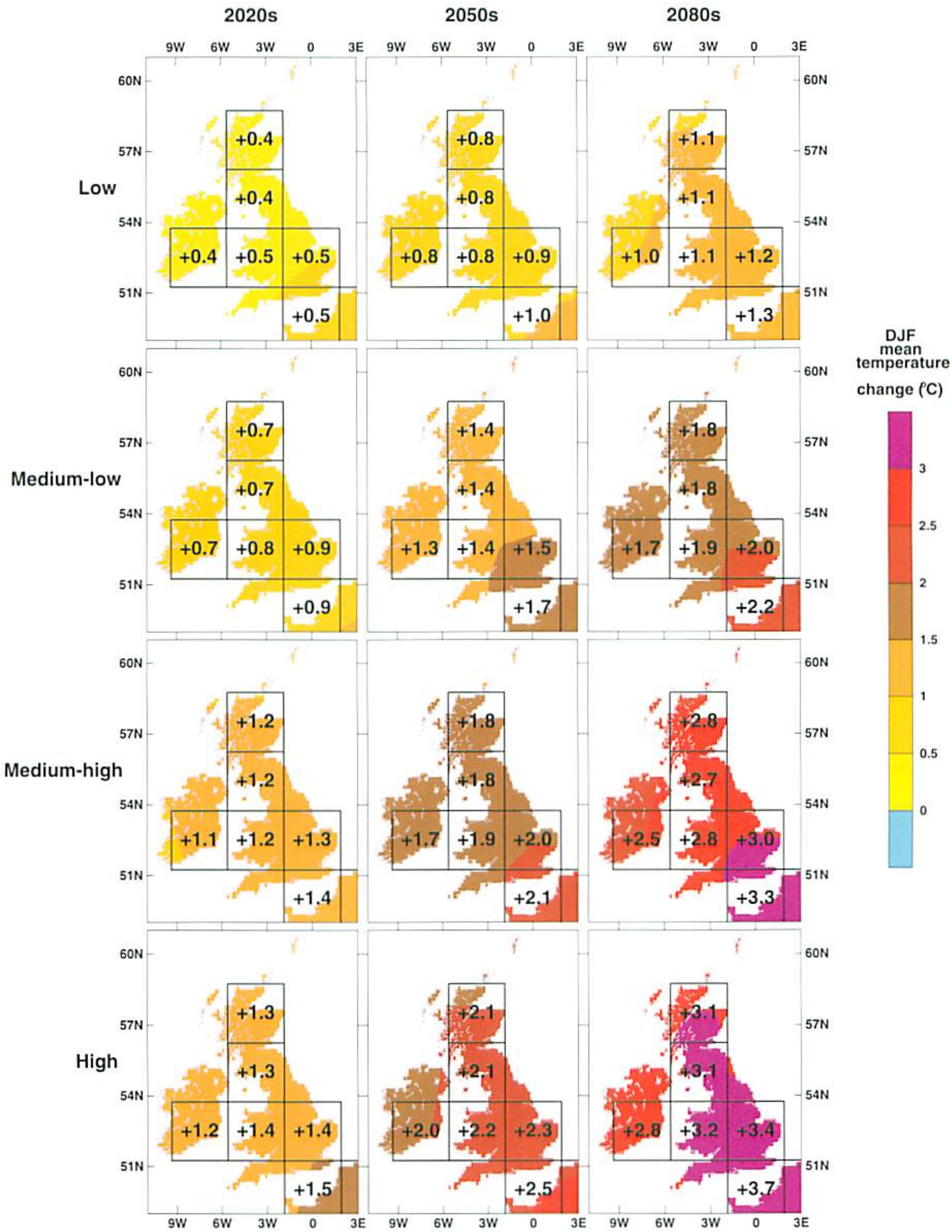


Figure 14: As Figure 13, but for winter mean temperature.

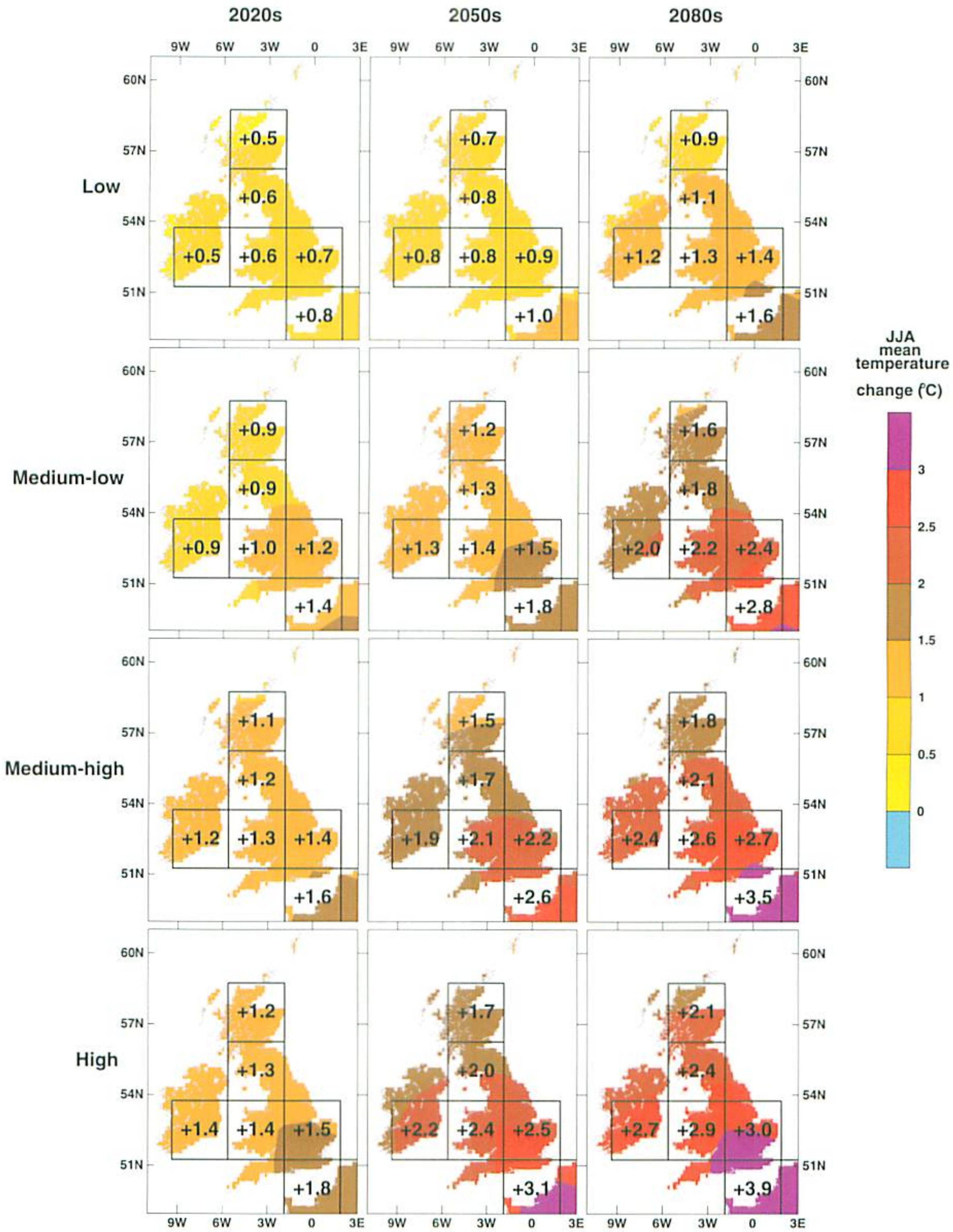


Figure 15: As Figure 13, but for summer mean temperature.

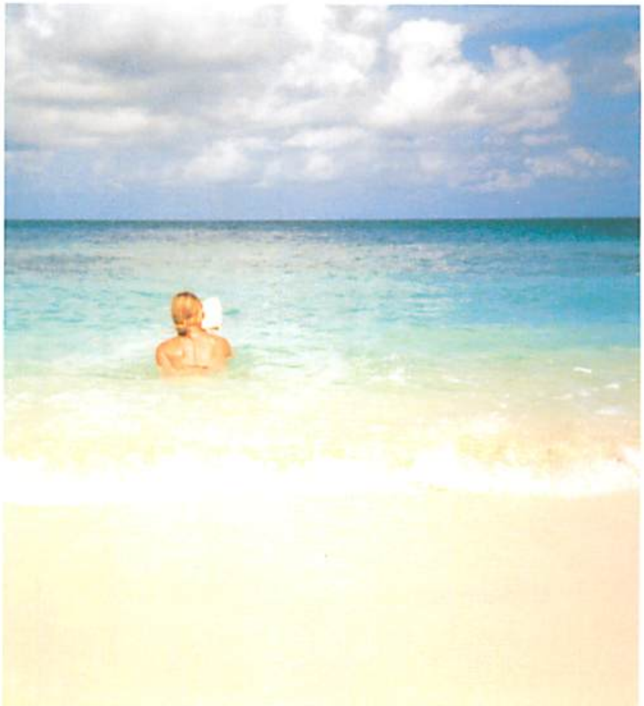
4.2 Changes in Precipitation

Figures 16, 17 and 18 show the equivalent changes in total precipitation. The patterns of precipitation change are less consistent between seasons and scenarios than for temperature. Annual and winter precipitation increases for all periods and scenarios, although the annual increases by the 2080s for the **Low** and **Medium-low** scenarios are very modest at only a few per cent. Winter precipitation increases are larger reaching 20 per cent or more for the 2080s in the **High** scenario. Such winter precipitation increases are certainly larger than natural variability (see Chapter 7).

For summer, there is a general tendency for drying in the south of the UK and wetting in the north. These changes are modest, however, and probably only significant in the southeast of the country and for the 2080s period in the **Medium-high** and **High** scenarios (see Chapter 7). The two other seasons (spring and autumn) are not shown here, but autumn shows broadly similar patterns of change to winter, while precipitation changes in spring are generally very small (not significant) except perhaps for the wetting by the 2080s in the **Medium-high** and **High** scenarios.

4.3 Changes in Temperature Extremes

The maps shown above indicate changes in mean climate. For many purposes, however, it is the changes in the frequency of extreme events that will be more important. Chapter 5 examines a number of such indices for the **Medium-high** scenario, but here we show one example relating to an annual temperature anomaly. Table 5 shows the changing probabilities that the annual temperature anomaly experienced in the Central England in 1997 will be exceeded in the future (1997 was the third warmest



1997 was a very warm year in the UK and resulted in different patterns of recreation and tourism (photo: David Viner)

year ever recorded in the UK, nearly 1.1°C warmer than the average 1961-90 temperature).

Under all four scenarios, such an annual anomaly becomes much more frequent, occurring once per decade by the 2020s under the **Low** scenario and nearly seven times per decade under the **High** scenario. By the 2080s, virtually every year is warmer than 1997 in the **Medium-high** and **High** scenarios, and 56 and 88 per cent of years are warmer than 1997 in the **Low** and **Medium**-low scenarios.

	1961-90	2020s	2050s	2080s
Low	6	13	26	56
Medium-low	6	47	74	88
Medium-high	6	59	85	99
High	6	67	89	100

Table 5: Percentage of years in southern UK exceeding an annual-mean temperature anomaly of +1.06°C above the 1961-90 mean (i.e., the observed 1997 annual anomaly for Central England) under the four UKCIP98 scenarios. Probabilities are all calculated using pooled results from the four HadCM2 ensemble experiments for the two southern UK gridboxes. The 1961-90 values are based on model simulations and not on observations.

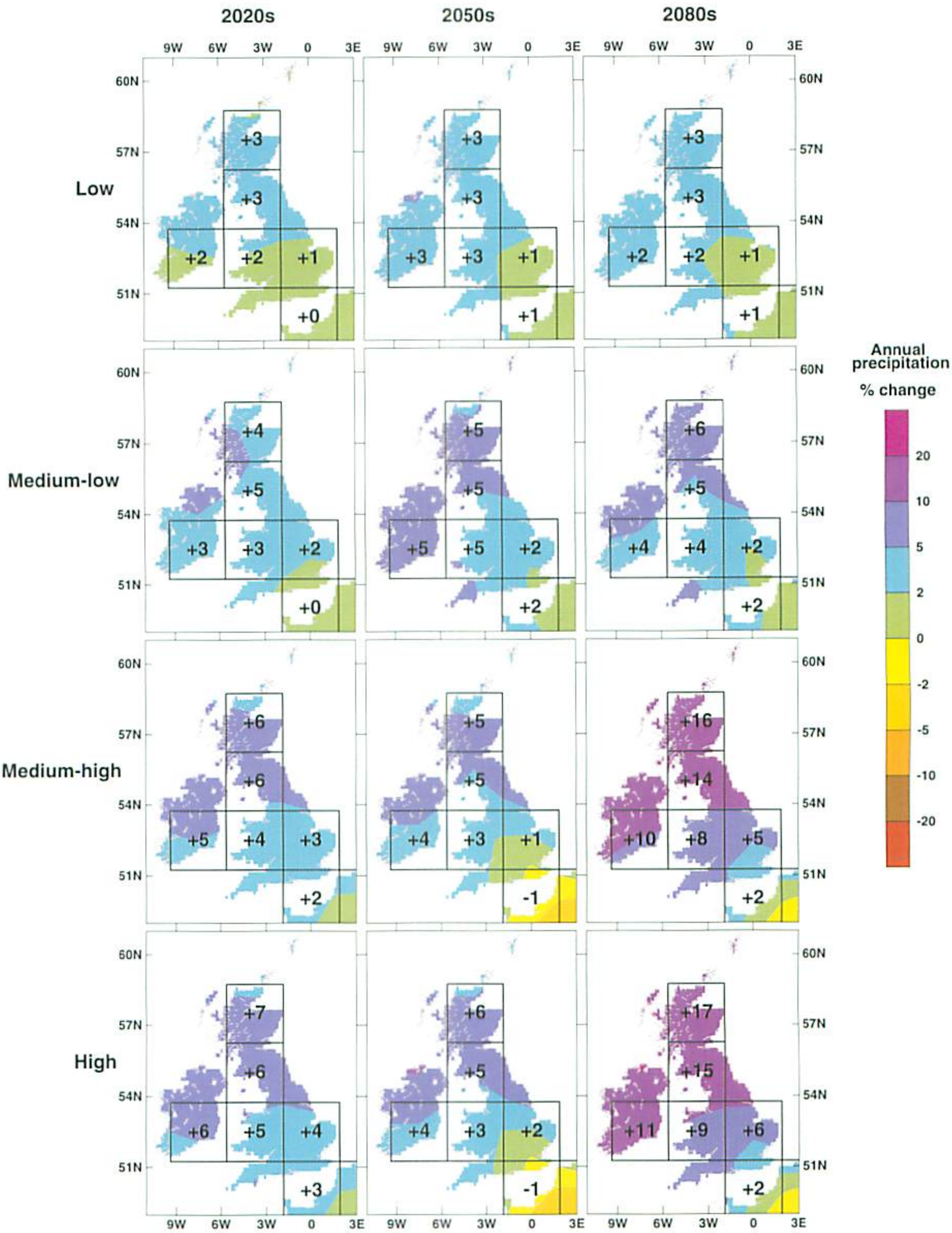


Figure 16: As Figure 13, but for annual precipitation expressed as per cent change from the 1961-90 mean.

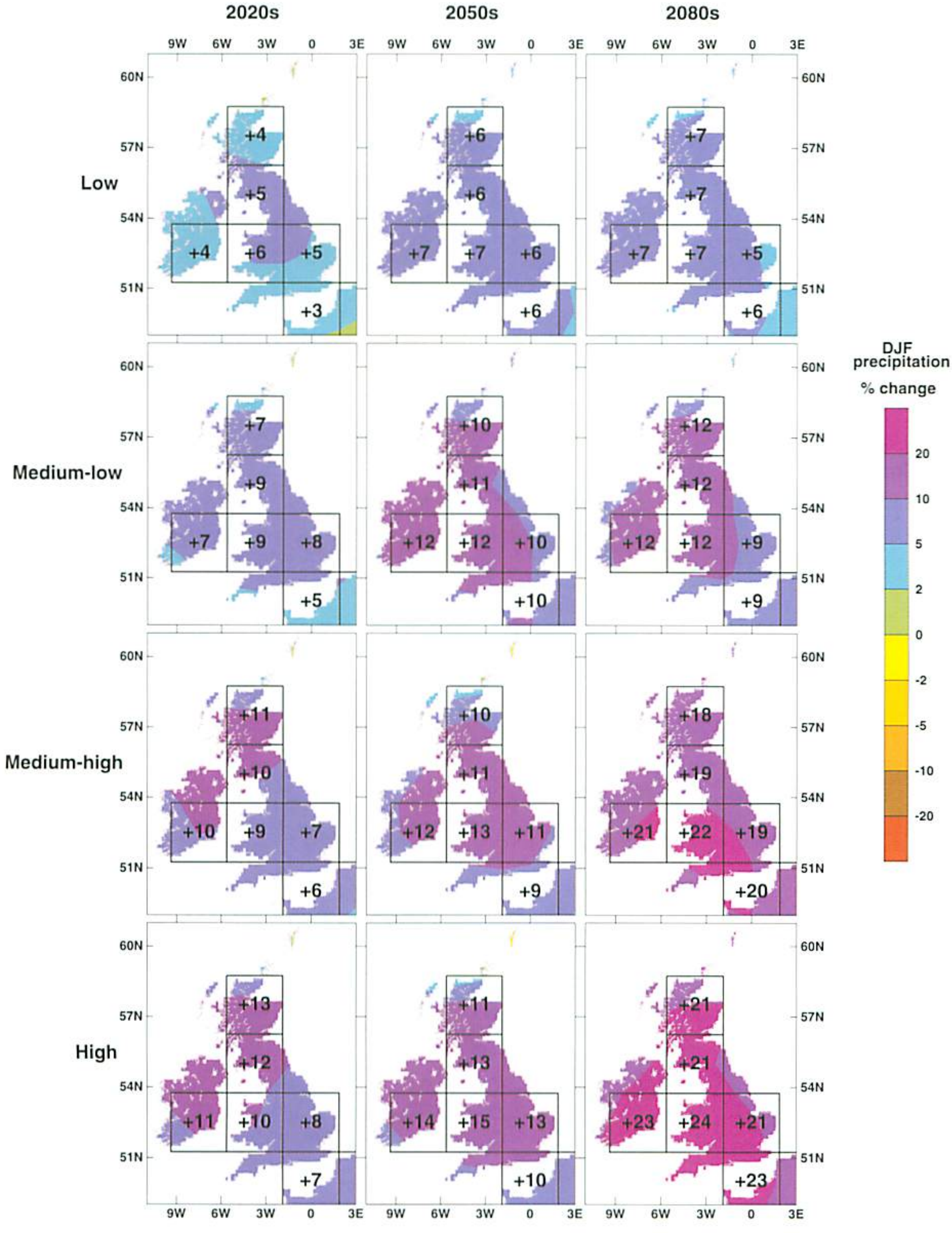


Figure 17: As Figure 16, but for winter precipitation.

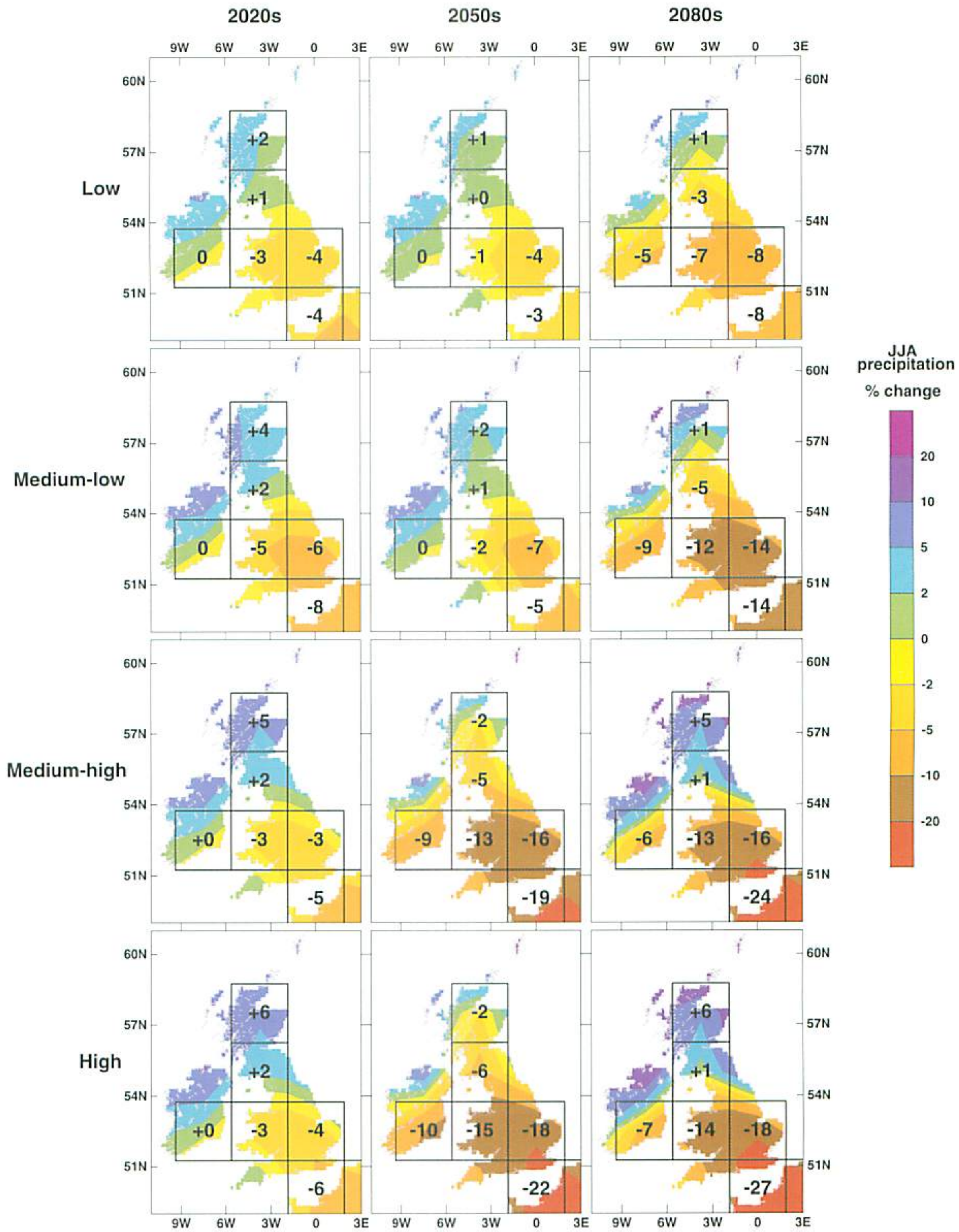


Figure 18: As Figure 16, but for summer precipitation.

4.4 Changes in CO_2 and Sea-level

The changes in global atmospheric carbon dioxide concentration for the UKCIP98 scenarios have been shown in Table 4. Those prevailing over the UK will be very similar. Thus by the 2020s, carbon dioxide concentrations for the **Medium-low** and **Medium-high** scenarios would be, respectively, 19% and 34% higher than the 1961-90 average of 334ppmv, and by the 2080s, 49% and 109% higher.

Changes in mean sea-level around the UK coast will also be very similar to the global-mean shown in Table 4. Although there will be regional differences in the rate of sea-level rise due to climate change, for the UK region the HadCM2 experiments generate results that are generally within 2 or 3 cm of the global-mean. For the 2050s, for example, sea-level rise around the UK coast is about 10 per cent higher than the global-mean. This occurs due to regional changes in ocean currents and atmospheric pressure that lead to greater rates of thermal expansion and water accumulation in the northeast Atlantic compared to the global average. What is more important when evaluating these sea-level changes, however, is to consider natural vertical land movements. These are the rates at which the coastline is rising or falling as a result of isostatic adjustments. Much of southern UK is sinking and much of northern UK is rising. We show some representative rates for the UK coastline in Table 6, alongside the climate-induced changes in sea-level for the 2050s. The two most extreme regions for vertical land movements are East Anglia - sinking by 9cm by the 2050s - and western Scotland - rising by 11cm. Under the lower scenarios of climate-induced sea-level rise these natural land movements can be very significant in exacerbating or reducing the estimated climate-induced change in mean sea-level around the UK coast.

Parts of the UK coastline are already vulnerable to coastal erosion. Rising sea-levels and more frequent storms would increase this vulnerability. [Photo: Mike Hulme].

	Low		Medium-low		Medium-high		High	
	Climate	Net	Climate	Net	Climate	Net	Climate	Net
West Scotland	13	2	20	9	28	17	74	63
East Scotland	13	8	20	15	28	23	74	69
Wales	13	18	20	25	28	33	74	79
English Channel	13	19	20	26	28	34	74	80
East Anglia	13	22	20	29	28	37	74	83

Table 6: Representative changes in sea-level (cm) around the UK coast by the 2050s due (i) to global climate change only ('Climate') and (ii) to the combined effect of climate and natural land movements ('Net'). The global-mean climate-induced sea-level changes shown in Table 4 are used here, but adjusted by 10 per cent to account for slightly higher rates of increase around the UK coastline. Vertical land movement estimated from data provided by Ian Shennan, University of Durham. Changes are with respect to average 1961-90 levels.

Chapter 5: More Detail for the Medium-High Scenario

The four UKCIP98 climate scenarios presented in Chapter 4 have been deliberately chosen to span a range of possible future climate changes for the UK. Attaching relative probabilities to these scenarios is difficult. In this Chapter, we show more details for the **Medium-high** scenario not because it necessarily represents our best-guess at the future, but because more modelling results are available for this scenario and because it is helpful to analyse a wider sample of climate indices for at least one of the UKCIP98 scenarios. Equivalent detail for the other scenarios is provided on the CD-ROM.

The **Medium-high** scenario is based on the HadCM2 experiments which use a 1 per cent per annum growth in atmospheric greenhouse gas concentrations over the next century, similar to the IS92a emissions scenario[10]. In this chapter, results are shown for more climate variables than just mean temperature and precipitation, for analyses of daily extremes and interannual climate variability, and for analyses of derived variables such as storm-surges and lightning strikes.

5.1 Mean Seasonal Climate

Figures 19 to 25 show seasonal and annual mean changes for seven surface climate variables for the thirty-year periods centred on the 2020s, 2050s and 2080s:

- diurnal temperature range
- vapour pressure
- relative humidity
- incident short-wave radiation
- total cloud cover
- mean 10m wind speed
- potential evapotranspiration

Potential evapotranspiration changes are calculated using the Penman formula (assuming a short grass covered surface) with temperature, vapour pressure, radiation and wind speed as inputs. All other variables are extracted directly from HadCM2. We discuss these changes - as well as the change in mean temperature and precipitation shown in Figures 13 to 18 - by season and summarise our conclusions in Table 7.

Winter sees a small, but consistent, decrease in diurnal temperature range across the UK, a change consistent with the increase in cloud cover and precipitation. This decrease in diurnal temperature range is uniform across the UK and amounts to about 0.3°C by the 2080s. Vapour pressure increases more rapidly in southern UK (+2 hPa by the 2080s) with slightly smaller increases in the north. But with increasing mean temperatures, relative humidity changes little. Short-wave radiation decreases by 1 or 2 Wm^{-2}, a change consistent with increased cloudiness and precipitation. Changes in mean seasonal wind speeds are more variable, both by region and over time. There are modest increases in wind speed over England and Wales by the 2080s, but small decreases over Scotland and N.Ireland. The anthropogenic signal is not well defined for winter wind speed. Potential evapotranspiration (PE) increases in winter, but mostly during the last decades of next century by which time winter PE may be 15 to 20 per cent higher. Winter PE seems most sensitive to temperature and wind speed changes.

Spring also sees reductions in diurnal temperature range, but with a tendency for larger decreases over northern UK than in the south. These patterns are again closely correlated with cloud cover changes. Vapour pressure increases are slightly smaller in absolute terms than in winter, but again the rise in mean temperature means that relative humidity remains quite stable, with just a hint of an increase over the north and west of the country. Changes in short-wave radiation show a strong gradient between the northwest - decreases - and the southeast - increases. These patterns of radiation change exaggerate the pattern of change in cloud cover. Wind speeds in spring decrease by 1 or 2 per cent across the UK, but again these patterns show large changes from one 30-year time-slice to another. PE in spring increases everywhere in the UK and, as with the change in radiation, there is a strong contrast between Scotland (2 to 4 per cent increases by the 2080s) and England and Wales (5 to 12 per cent increases).

10 *Unless stated otherwise, we show results for the average of the four identical experiments performed for this scenario by the Hadley Centre. This is called the 'ensemble-mean' result. We analyse the differences between the four individual ensemble members in Chapter 7.*

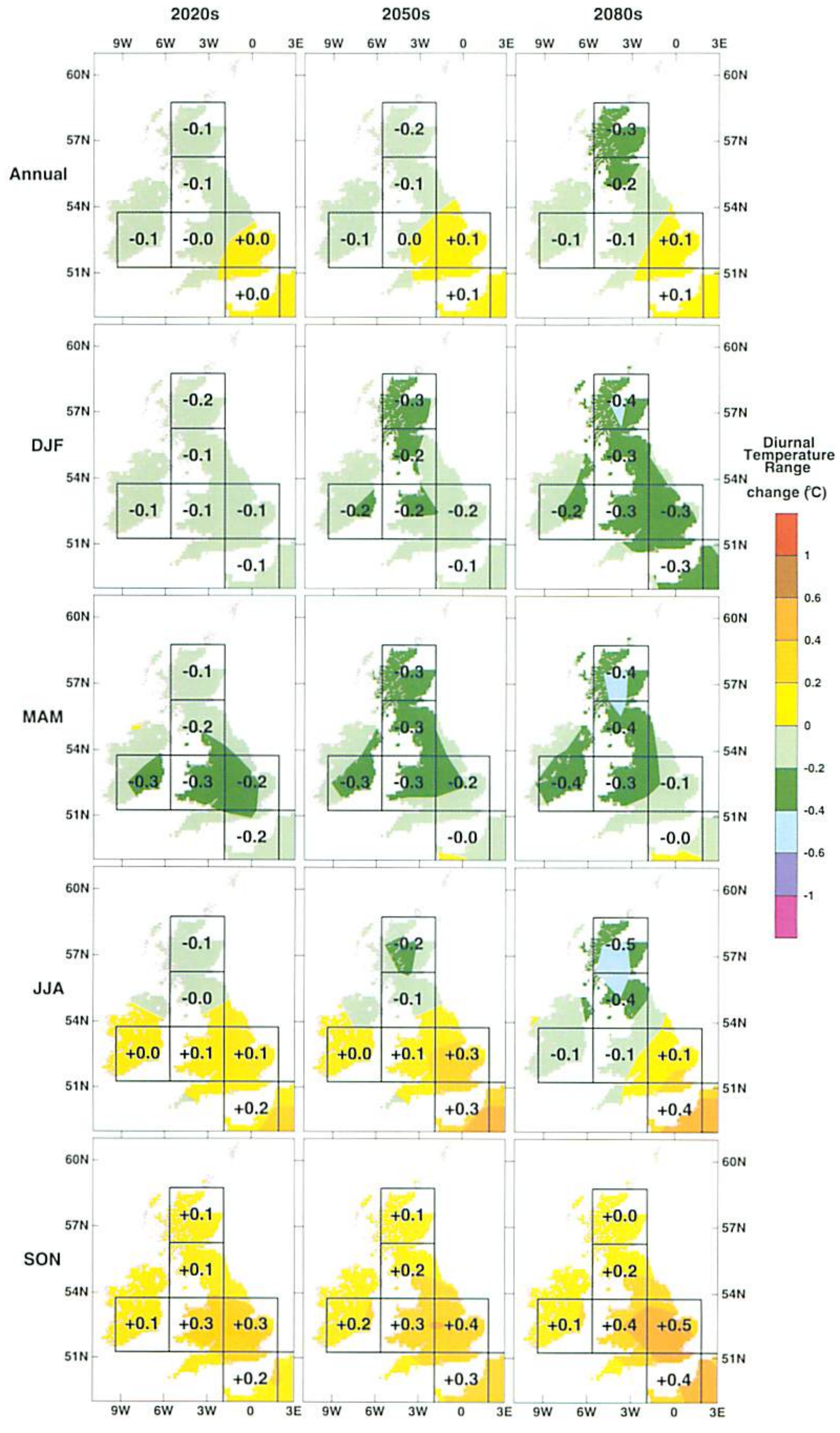


*Figure 19: Change in mean annual and seasonal diurnal temperature range (wrt 1961-90) for thirty-year periods centred on the 2020s, 2050s and 2080s for the **Medium-high** scenario. The background field is interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK.*

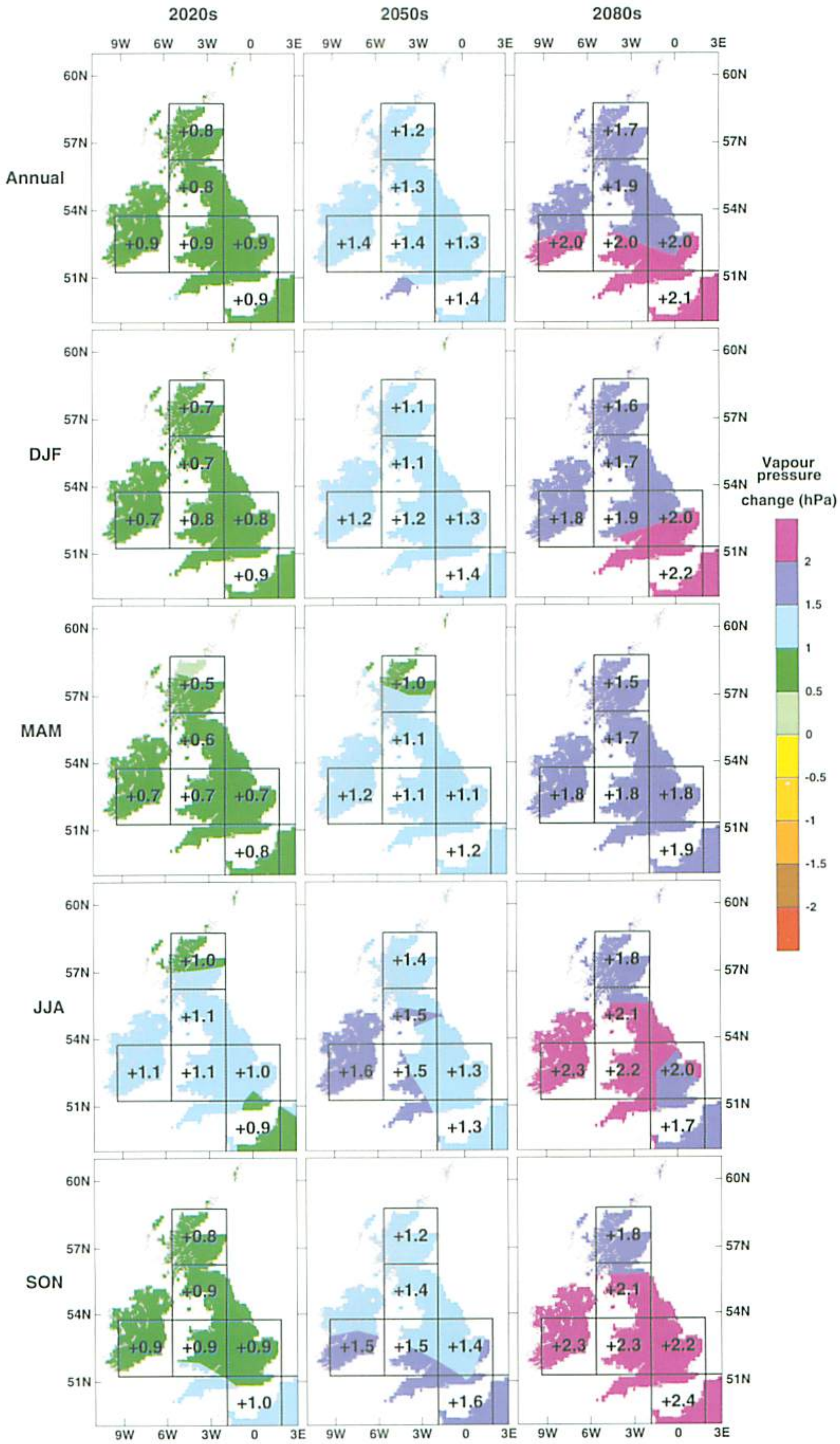


Figure 20: As for Figure 19, but for vapour pressure.

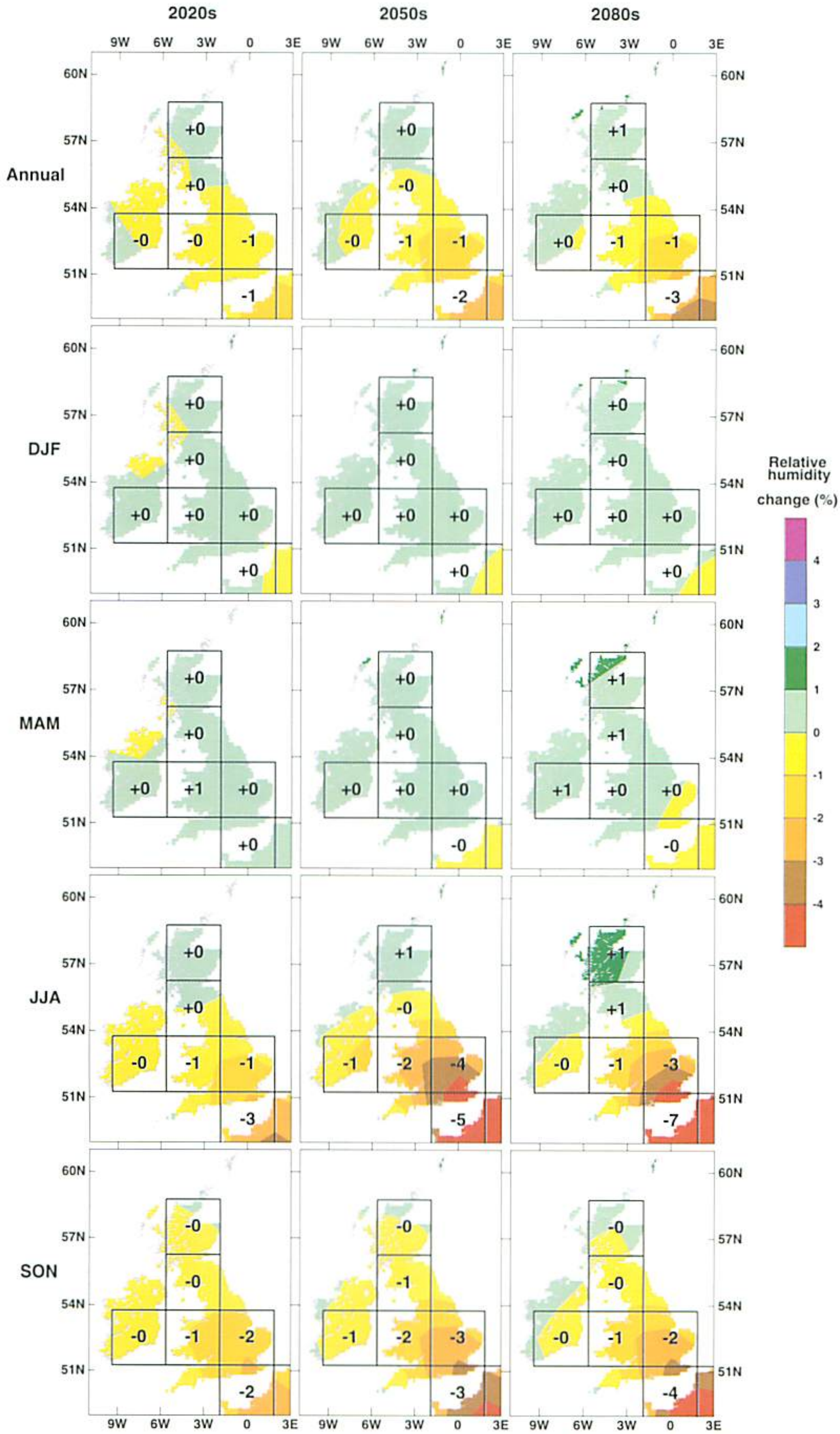


Figure 21: As for Figure 19, but for relative humidity.

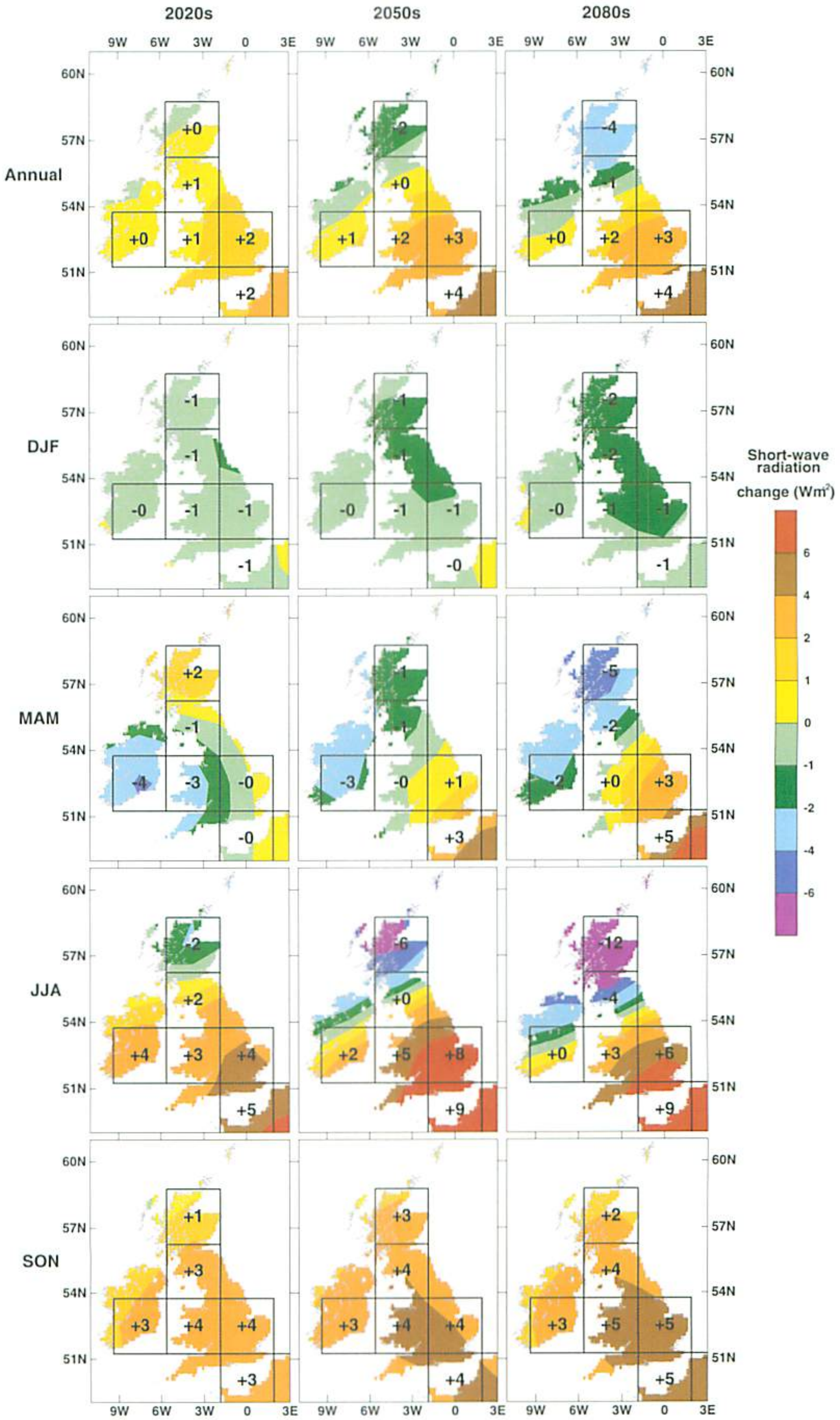


Figure 22: As for Figure 19, but for incident short-wave radiation.

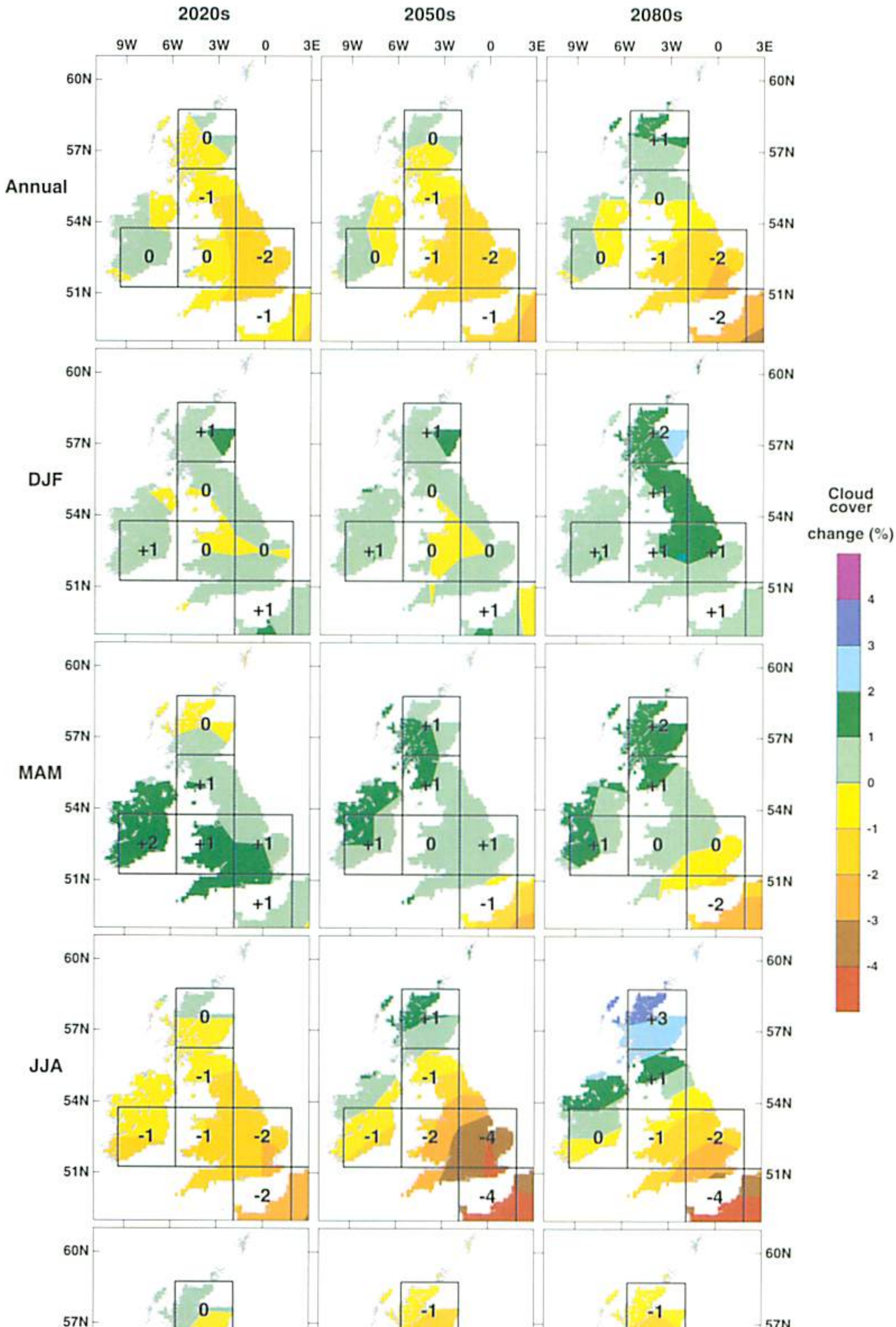


Figure 23: As for Figure 19, but for cloud cover.

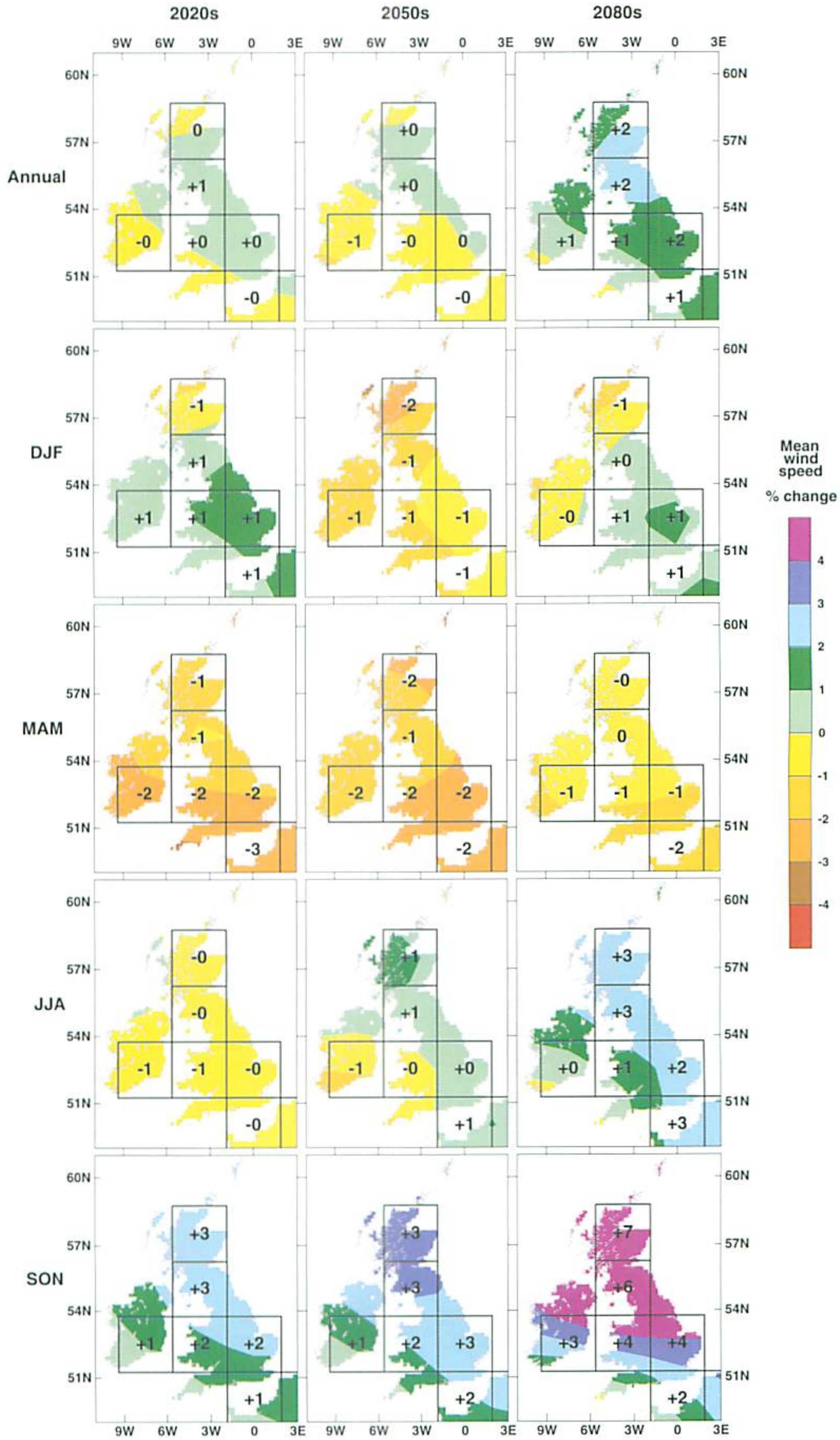


Figure 24: As for Figure 19, but for 10m wind speed.

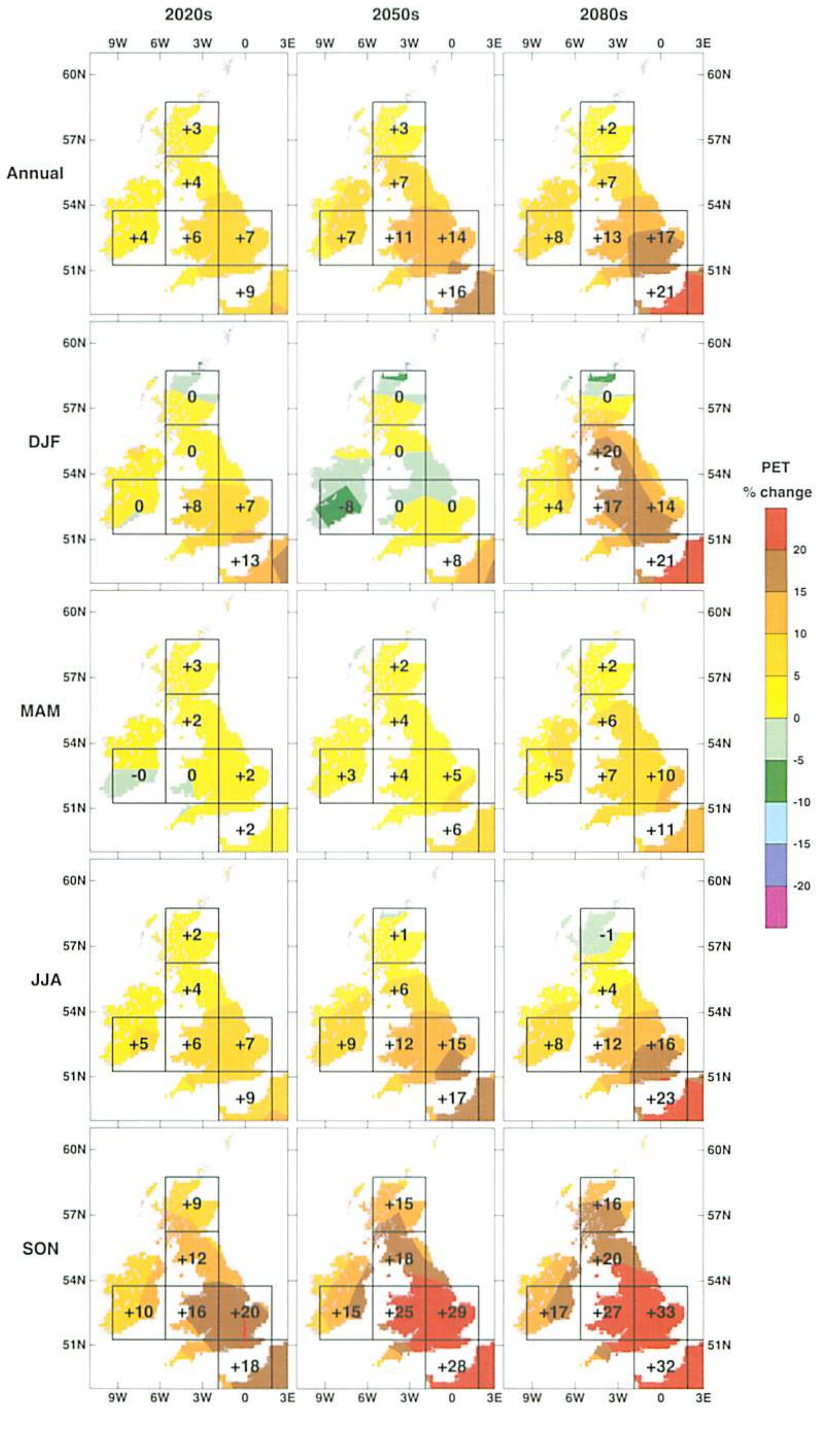


Figure 25: As for Figure 19 but for potential evapotranspiration.

	Winter	Spring	Summer	Autumn
Diurnal temperature range	Small decrease	Decreases, more in N than S	Decreases, except in SE	Large increases
Precipitation	Large increases	Little change	Decreases in S, slight increase in N	Large increases
Vapour pressure	Increases, more in S than N	Small increase	Increases	Increases
Relative humidity	Stable	Stable	Variable, with decreases in S	Small decrease in S
Radiation	Decreases	Increase in SE, decrease in NW	Increase in SE, decrease in NW	Increase
Wind speed	Variable changes	Slight decrease	Slight increase	Increases, specially in N
Potential evapotranspiration	Increases	Increases, especially in SE	Increases in S, stable in N	Large increases

Table 7: A summary of seasonal changes for some selected climate variables for the **Medium-high** *scenario.*

Summer diurnal temperature range increases slightly in the southeast of England, but decreases almost everywhere else. In general, these summer changes in diurnal temperature range match changes in cloud cover; summer cloudiness decreases by a few percentage points by the 2080s. Vapour pressure increases match those occurring in winter in absolute terms, yet relative humidity increases slightly in summer over Scotland, but decreases by a few per cent over England and Wales. This pattern of change in relative humidity matches that found in the map of seasonal precipitation change (Figure 18). The gradient of change in short-wave radiation found in spring is even more exaggerated in summer, the pattern again matching that found in cloud cover change. Radiation increases by several Wm^{-2} over England and Wales by the 2080s, but decreases by a larger amount over Scotland. Mean wind speed increases by 1 to 3 per cent in summer by the 2080s, but as with winter and spring, there is little consistency in this pattern from decade-to-decade. The pattern of potential evapotranspiration change in summer suggests a strong influence of radiation on PE. PE increases by up to 15 per cent over southern England, but remains quite stable over Scotland. These increases in PE in southern England will compound the effect of the summer precipitation decreases shown in Figure 18 on water availability. In summer, Scotland experiences small increases in precipitation and little change in PE, therefore the water balance will remain favourable.

Finally, **autumn** sees the largest increases in diurnal temperature range, these increases amounting to nearly 0.5°C over England by the 2080s. As in all other seasons, the patterns of diurnal temperature range and cloud cover changes are well matched. Vapour pressure and relative humidity changes in autumn are similar to those in summer, southern UK seeing a small decrease in relative humidity. Autumn is the only season with increases in radiation across the whole country, these increases reaching 2 to 5 Wm^{-2} by the 2080s. The uniform increase in radiation parallels the uniform decrease in autumn cloud cover which occurs despite the increased seasonal precipitation shown in Figure 39. Seasonal wind speed changes in autumn are the largest of all the seasons, Scotland seeing increases of up to 7 per cent. The increase in autumn wind speed is consistent across all three time-slices, unlike the other seasons. The combination of these wind speed increases and the increase in radiation means that PE increases in the autumn across the whole of the UK by between 10 and 30 per cent. The PE changes as early as the 2020s are already between 10 and 20 per cent.

5.2 Climate Variability, Seasonal Climate Anomalies and Daily Weather Extremes

In the previous section, we presented changes in mean (thirty-year) seasonal or annual climate. Changes in inter-daily, interannual and inter-decadal climate variability will also be very important for determining the likely impacts of climate change and the subsequent adaptation adjustments. In this section we present results from some analyses that examine changes in the variability regime and in the frequency of selected weather extremes for the UKCIP98 **Medium-high** scenario.

Figures 26 and 27 show the change in the year-to-year variability of mean seasonal and annual climate for mean temperature and precipitation as measured by the per cent change in the interannual standard deviation. Given the climate warming of this scenario (*cf.* Figures 13 to 15), one would expect an increase in this measure of temperature variability since the standard deviation is related to the mean. Figure 26 shows, however, that changes in temperature variability differ by season. Winter temperatures become less variable (probably because of reduced Arctic sea-ice and Eurasian snow cover), while summer temperatures become more variable (probably because of a drier land surface), especially over the southern UK. This contrast can also be seen in the graphs plotted in Figure 33. Precipitation variability, however, increases almost everywhere and in every season (Figure 27) despite the fact that precipitation increases in winter and autumn and decreases in spring and summer (*cf.* Figures 16 to 18). Changes in the day-to-day variability of mean temperature and precipitation are provided on the CD-ROM.

Partly related to these changes in interannual climate variability are the changing probabilities of certain seasonal climate extremes. Table 8 shows the changing likelihood of four different climate anomalies occurring in the southern UK for three future periods. For example, an August as hot as that observed in 1997 - the second hottest August on record with an anomaly of +3.4°C - occurs on average four times a decade by the 2080s, compared to once every 50 years under the modelled 1961-90 climate. The observed annual temperature anomaly of 1997 is achieved in virtually all years by the 2080s under this scenario (*cf.* Table 5). For precipitation, the probability of summers experiencing deficits of 50 per cent or more increases very substantially and occurs once per decade in the future, compared to once a century under modelled present climate. In contrast, the probability of successive dry years - defined as a two-year precipitation deficit of 10 per cent or more - changes little in the future and by the 2080s actually becomes slightly rarer. This is because summer precipitation deficits are more than compensated by increased precipitation in other seasons. These results are consistent with the changes in mean seasonal and annual climate shown in Figures 16 to 18 for the **Medium-high** scenario.

	1961-90	2020s	2050s	2080s
Mean temperature				
A *hot* '1997-*type*' *August* (+3.4°C)	2	15	32	40
A *warm* '1997-*type*' *year* (+1.06°C)	6	59	85	99
Precipitation				
Summer precipitation below 50% of average	1	7	12	10
A two-year precipitation total below 90% of average	12	11	14	6

Table 8: Percentage of years experiencing various climate extremes across southern UK for present climate (1961-90) and for three future thirty-year periods for the ***Medium-high*** *scenario. Probabilities are all calculated using pooled results from the four HadCM2 ensemble experiments for the two southern UK gridboxes. Anomalies are with respect to the average 1961-90 climate. The 1961-90 values are based on model simulations and not on observations.*

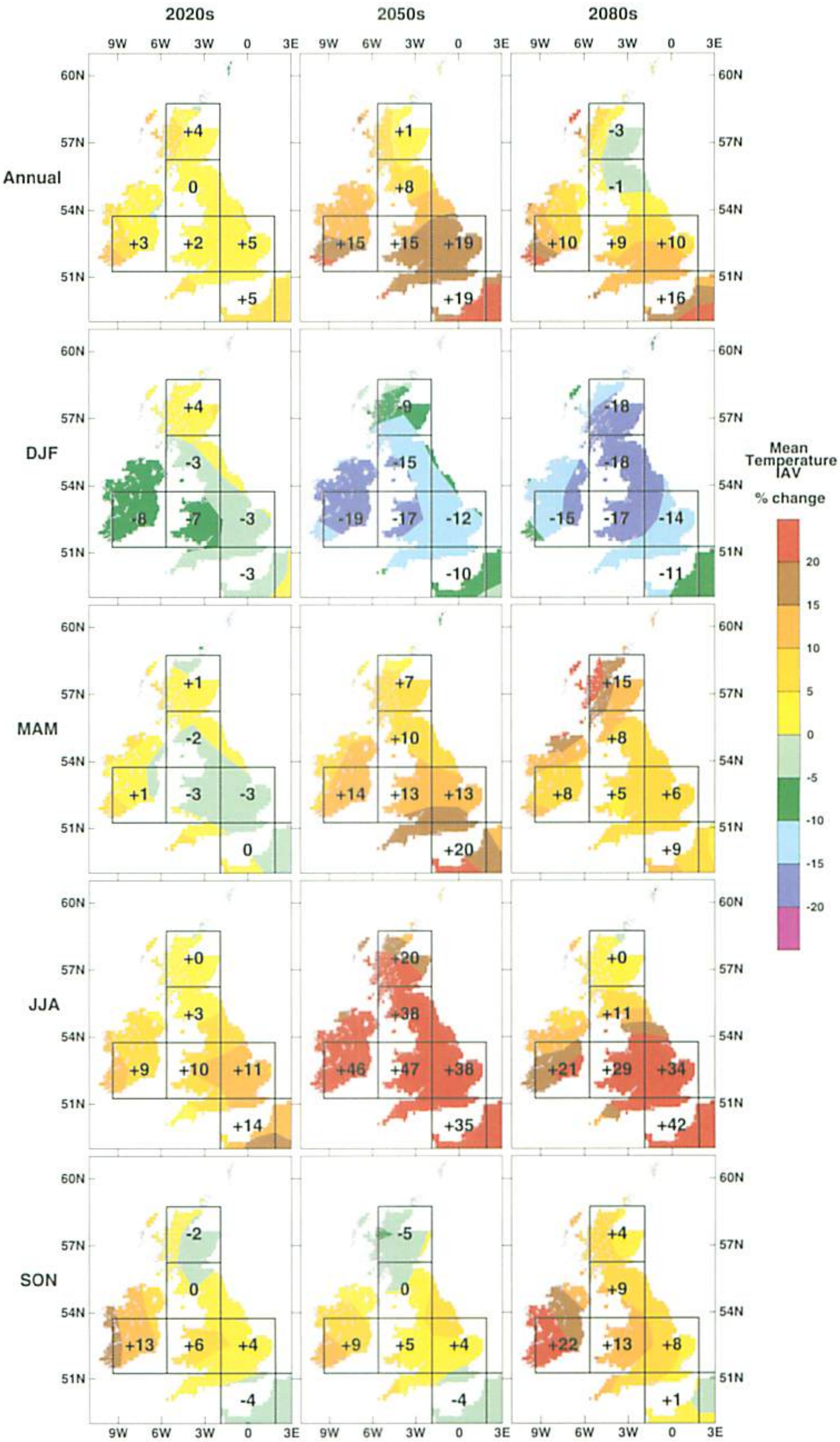


Figure 26: Changes in interannual variability in mean annual and seasonal temperature (wrt 1961-90) for thirty-year periods centred on the 2020s, 2050s and 2080s for the ***Medium-high*** *scenario. Changes are from the pooled results of four HadCM2 ensemble experiments and are calculated as the per cent change in the standard deviation. The background field is interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK.*

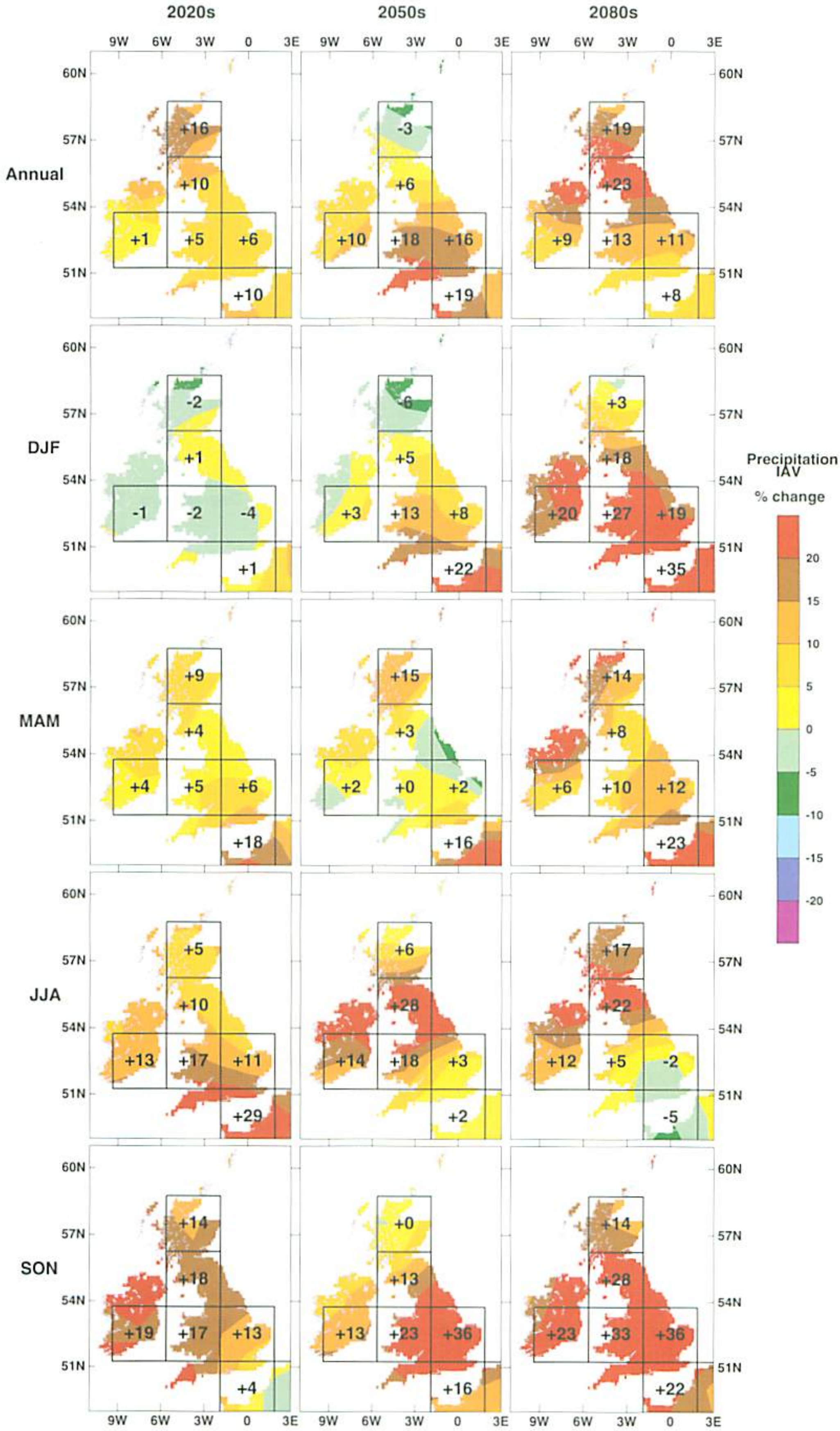


Figure 27: As for Figure 27, but for precipitation.

Changes in accumulated degree days above or below specified thresholds will also change as the temperature regime changes. Figure 28 shows the per cent changes in the annual mean number of degree days above or below three specified temperature thresholds. The number of degree days for a minimum temperature below freezing (relevant, for example, for road maintenance) decreases by between 70 and 80 per cent across the UK by the 2080s, while the degree days for a maximum temperature above 25°C (relevant for air-conditioning) more than trebles by the 2080s. Degree days for mean temperature above 5.5°C (indicative of the plant growing season) increase by between 3 and 7 per cent per decade over the next century.

Finally in this section, we examine changes in occurrence probabilities for daily mean wind speed (Figure 29) and daily precipitation intensity (Figure 30). We present these analyses for northern and southern UK and for the winter and summer seasons by the 2080s. The absolute thresholds of these quantities for given probabilities should be interpreted with caution since we are basing this analysis on climate model gridbox output, quantities that are quite different from those conventionally measured at individual meteorological stations (see Appendix 7). What can be gleaned from these diagrams, however, are the *relative* changes in these daily quantities by the 2080s period under the **Medium-high** scenario.

Over the northern UK, there are more frequent days with high summer wind speeds, but little change in winter daily wind extremes[11]. Over the southern UK there is little consistent change in the extreme daily wind regime in either summer or winter (Figure 29). These results of daily wind speed are broadly consistent with the mean seasonal changes shown in Figure 24.

Changes in the overall amount of precipitation will be accompanied by changes in the number and intensity of precipitation events. Over the northern UK, precipitation intensities increase in both winter and summer, the most intense events becoming perhaps several times more frequent than at present. This is likely to lead to greater risk of flooding. Over the southern UK, intensities increase only in winter. In summer in the south,

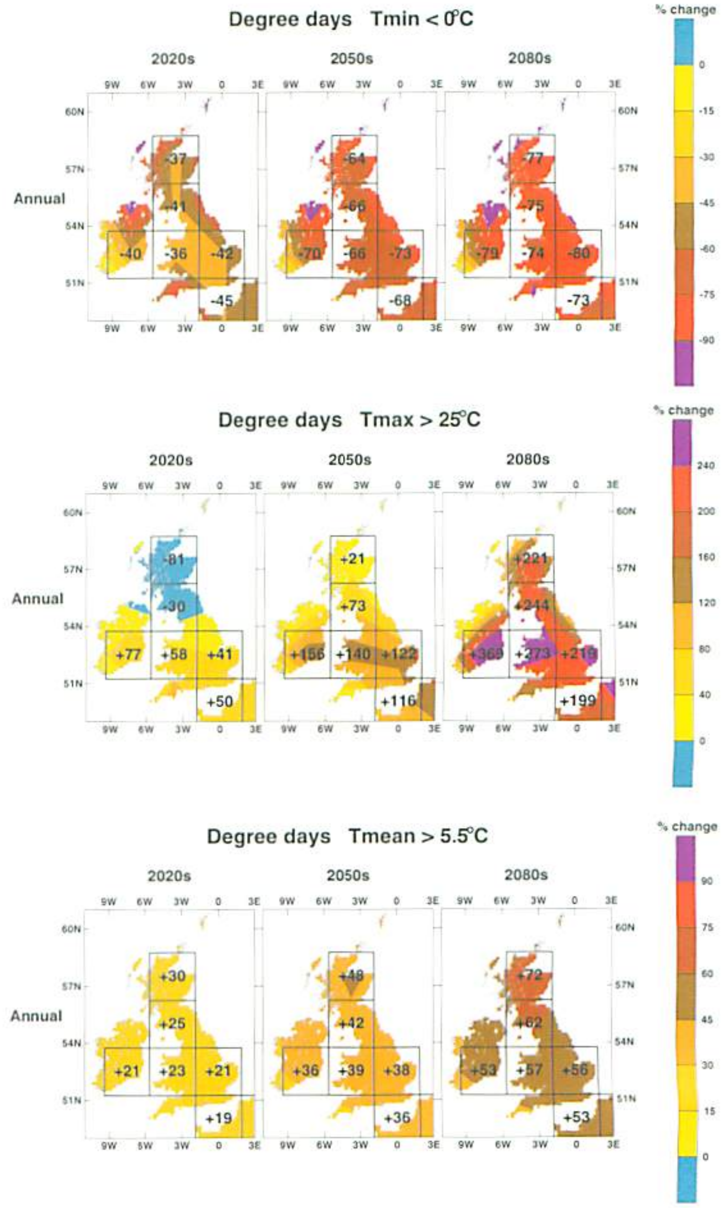


Figure 28: Changes in annual accumulated degree days for the 2020s, 2050s and 2080s for the ***Medium-high*** *scenario. The three temperature thresholds are: minimum daily temperature <0°C (top), mean daily temperature >5.5°C (middle), and maximum daily temperature >25°C (bottom). Data are extracted from one member of the HadCM2 ensemble. The background field is interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each land gridbox over the UK.*

11 *For high daily mean windspeeds (>10m/s), the maximum hourly windspeed is typically about 20 per cent greater than the daily mean windspeed and the maximum gust is about twice the daily mean windspeed. Assuming this relationship holds in the future, maximum hourly windspeeds and gusts under the* ***Medium-high*** *scenario would change by only 2 per cent at most.*

because there is a reduction in the overall amount of precipitation there are fewer high intensity precipitation events compared to the present climate (although the proportion of the seasonal summer precipitation that falls in intense events may increase).

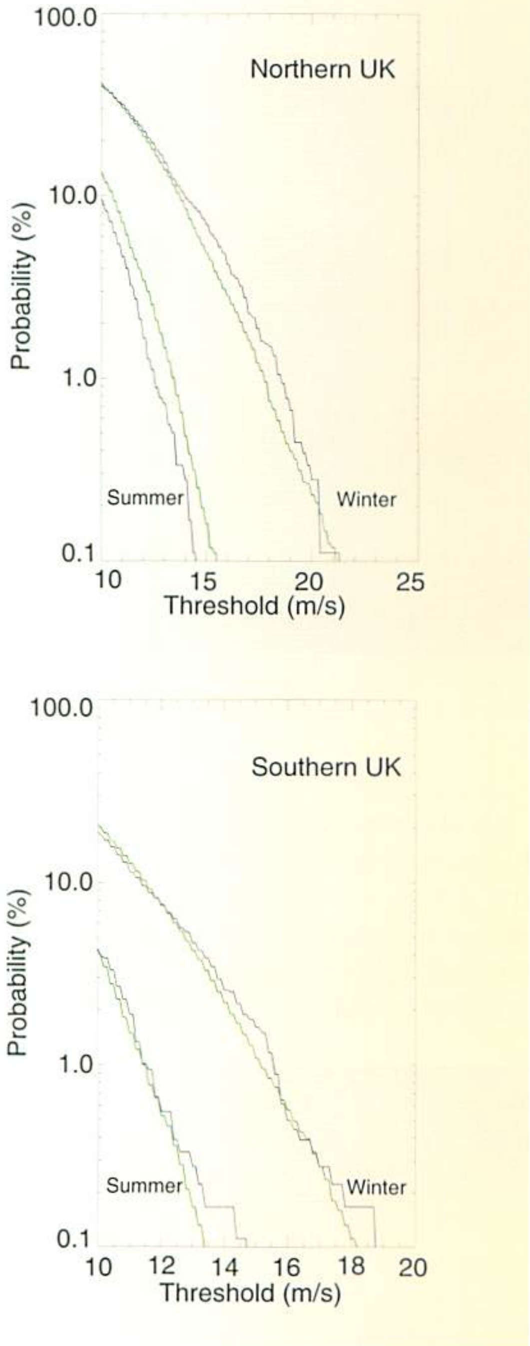


Figure 29: Change in estimated occurrence probalility (events per year) for winter and summer mean daily wind speed by the 2080s for northern (left) and southern (right) UK. Data are pooled from the four HadCM2 ensemble experiments. Black = 1961-90; Green = 2080s

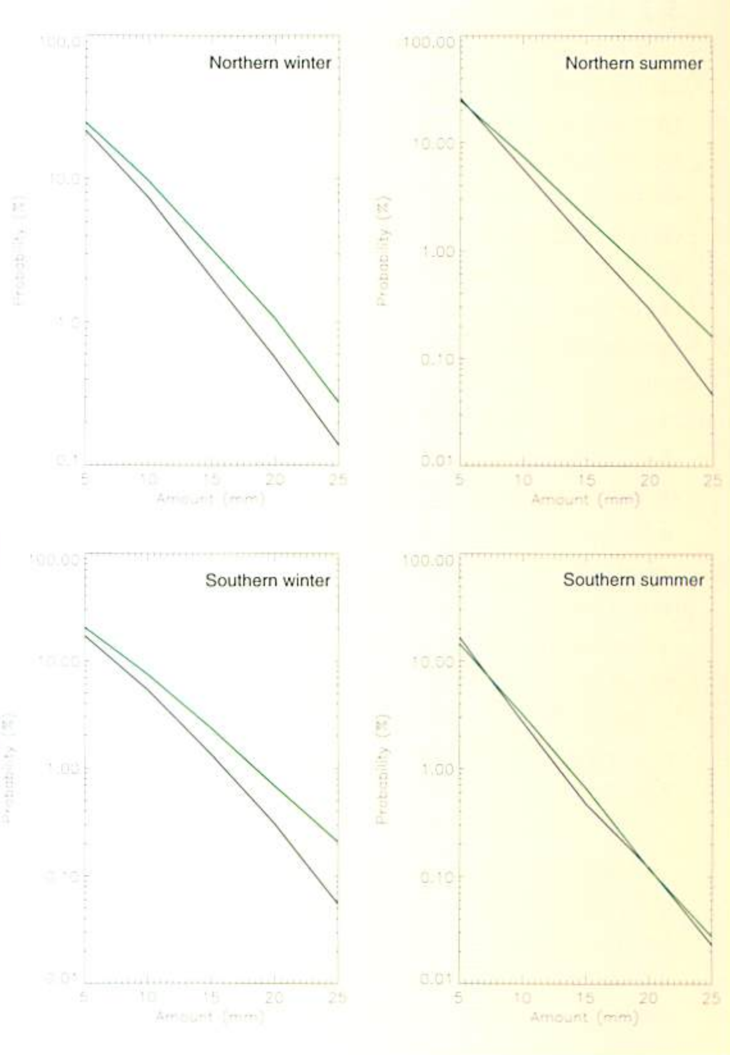


Figure 30: Change in estimated occurrence probability (events per year) for winter (left) and summer (right) daily precipitation intensity by the 2080s for northern (top) and southern (bottom) UK. Data are pooled from the four HadCM2 ensemble experiments. Black = 1961-90; Green = 2080s.

5.3 Other Climate-related Variables

In this section we present results from a number of analyses for climate variables or climate indices that are not directly generated by HadCM2, but which can be derived from its output. We start by showing the changes in the frequencies of three different categories of gales (Table 9): gales, severe gales and very severe gales. For the winter season, there is a suggestion that overall gale frequencies decline in the future, although very severe winter gales increase. Note that the changing sign of the changes in severe gale frequencies between the three periods indicates that a clear anthropogenic signal in severe gale frequencies is not easily detectable from the noise of natural climate variability. Summer gales are much less frequent (less than 2 per year) than winter gales and consequently any changes in summer gale frequencies are likely to be small. Nevertheless, by the 2080s there is a modest (~10 per cent) increase in the number of summer gales affecting the UK.

Related to this analysis of gale frequencies is the analysis of changes in airflow characteristics over the British Isles shown in Figure 31. Three aspects of airflow are analysed: flow strength, vorticity (i.e., anticyclonic or cyclonic flow) and flow direction. Figure 31 shows changes in these indices for the 2080s period, expressed as changes in the number of days per season experiencing different categories of each index. This analysis suggests a tendency for autumns to experience windier conditions, with a reduction in northerly and easterly flow and an increase in southwesterly and westerly flow. Summers become slightly more anticyclonic in character with more westerly and northwesterly flow, while winter and spring become slightly less anticyclonic. These changes in airflow characteristics may be important for certain aspects of the UK environment, for example air pollution levels in cities or episodes of acid deposition.

Air pollution hazards in cities, to which road traffic contributes greatly, will be influenced by changing frequencies of anticyclonic conditions

We also suggest possible changes in the frequency of lightning for the **Medium-high** UKCIP98 scenario. Lightning frequencies are related to convective thunderstorm activity. Although lightning frequency is not modelled explicitly in HadCM2, on the basis of sensitivity

	1961-90 Gales/year	2020s % change	2050s % change	2080s % change
Winter gales	10.9	-1	-9	-5
Winter severe gales	8.5	-1	-10	-5
Winter very severe gales	1.4	+8	-10	+11
Summer gales	1.8	+3	0	+14
Summer severe gales	1.1	0	-2	+15
Summer very severe gales	0.1	+25	-16	+9

Table 9: Changes in seasonal gale frequencies over the British Isles for the 2020s, 2050s and 2080s for the **Medium-high** *scenario shown as per cent changes from the 1961-90 mean. 1961-90 frequencies are calculated from climate model outputs and not from observations. Data are pooled from the four HadCM2 ensemble experiments.*

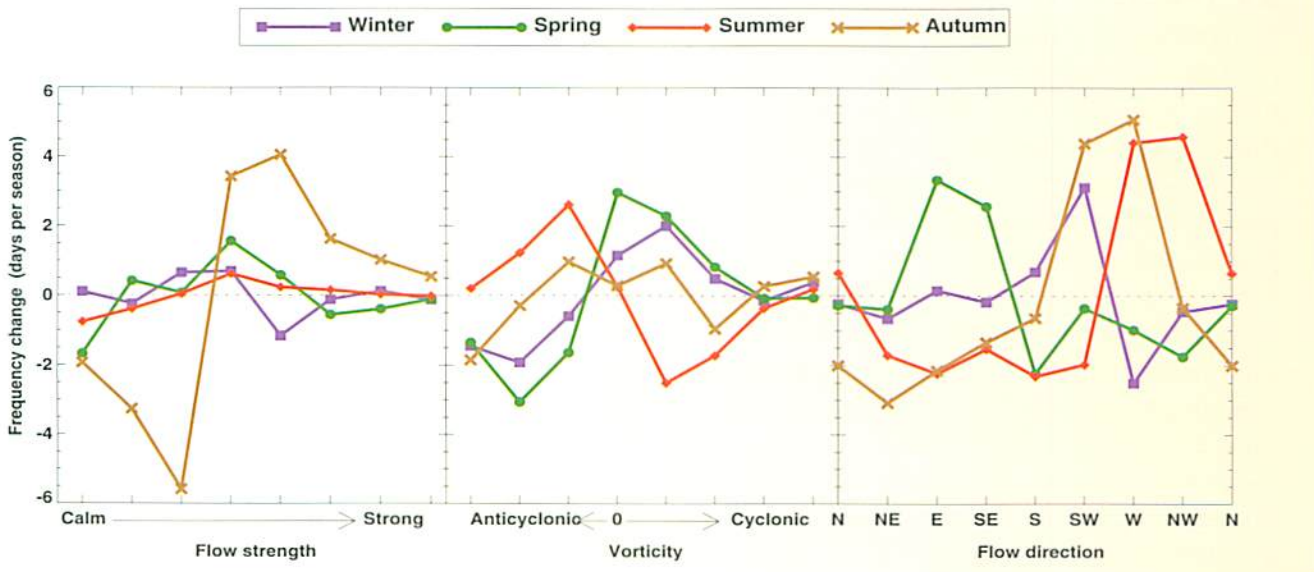


Figure 31: Changes in seasonal airflow characteristics (days per season) over the British Isles by the 2080s for the **Medium-high** *scenario. The three airflow indices describe strength of airflow, vorticity of the surface circulation and the airflow direction and results are representative of airflow conditions across the whole British Isles region. Data are extracted from one member of the HadCM2 ensemble.*

experiments performed in other climate modelling centres and the changes in convective precipitation estimated by the HadCM2 model, we suggest that by the 2080s lightning frequency over the UK may increase by about 20 per cent. This pertains to both intra-cloud and cloud-to-ground lightning frequencies. This conclusion is consistent with the picture of increasing precipitation intensities that emerged earlier.

Finally, we consider the effect of changes in mean sea-level for high tide-levels around the UK coast. Table 6 in Chapter 4 showed estimates of mean sea-level change for the UK under the various UKCIP98 scenarios. Here, we interpret what the **Medium-high** scenario of sea-level rise may mean for tide-level return periods for one part of the UK coastline - Harwich in East Anglia. In this simple analysis we assume no change in storminess, just a change in mean sea-level resulting from climate change (+28 cm by the 2050s) plus the net effect of vertical land movements (+13 cm for Harwich by the 2050s). For Harwich, a tide-level of 5.6 metres above datum becomes ten times more frequent by the 2050s, the 100-year return period falling to a 10-year return period (Figure 32). This result cannot be generalised to other parts of the UK coastline because of different rates of vertical land movement and because of different coastline and offshore topography. This example of Harwich perhaps presents one of the more extreme examples of how changes in mean sea-level can have major impacts on tide-levels.

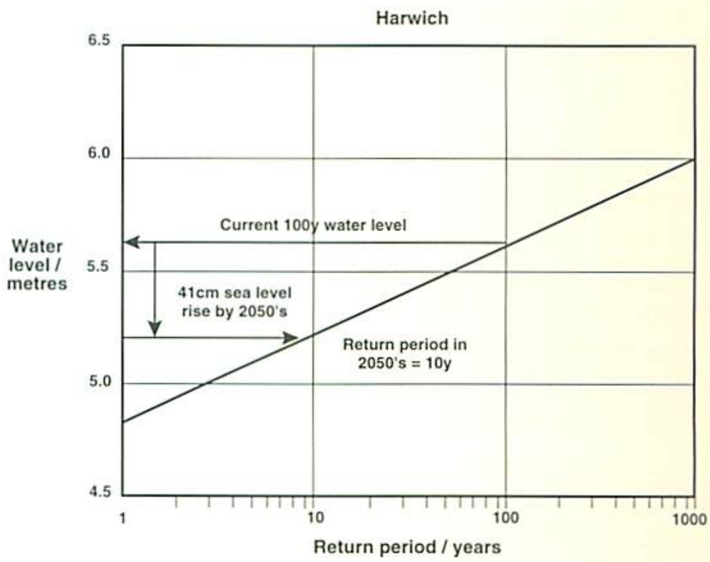


Figure 32: Estimated change in tide-level return period for Harwich in East Anglia assuming the 2050s **Medium-high** *mean sea-level rise of 28 cm, plus a 13 cm net rise due to land subsidence. The example highlighted shows that the 100-year return tide-level of +5.6 metres becomes the 10-year tide-level by the 2050s. No allowance is made for changes in storminess. Relationships based on data supplied by the Proudman Oceanographic Laboratory.*

5.4 The Evolution of UK Climate

Changes shown thus far are for discrete thirty-year periods in the future. These long-period averages hide the transient nature of the climate changes that will occur in the future - rather than jump from one average state to another, climate will change gradually with the underlying trends having natural year-to-year variations superimposed on top. Figure 33 illustrates one possible evolution of mean temperature and precipitation for winter and summer for southern UK under the **Medium-high** scenario. The year-to-year and decade-to-decade variability shown here is substantial and is a function of model-generated internal variability caused by natural ocean-atmosphere interactions. A more formal analysis of this natural variability relative to the anthropogenic component of the climate change is presented in Chapter 7.

The series shown in Figure 33 can be analysed to determine how frequently new seasonal temperature or precipitation records may be established for the southern UK in the future and these can be compared with the current seasonal record anomalies from the observed Central England Temperature and England and Wales Precipitation series (Table 10). Under this particular evolution of climate, new mean seasonal temperature records are established quite early in the scenario (model years '1996', '2002' and '2006' for summer and '2002/03' for winter[12]), but thereafter new records are only established on average once every two or three decades. New seasonal temperature records will not therefore be established every year or even every few years under the **Medium-high** scenario and there may be long periods when no new records are established.

For precipitation, the underlying trends are less clear then for temperature, but the graphs do show gradual drying in summer and wetting in winter - consistent with the mean seasonal changes shown in Figures 17 and 18. Again, however, new record dry or wet seasonal precipitation anomalies are only established on average every few decades and, in the case of precipitation, the modelled anomalies do not exceed - with one exception - the current observed record anomalies established in 1995 (for summer dryness) and 1914/15 (for winter wetness). This analysis could be completed for new daily temperature extremes, whether for maximum or minimum temperature, but this has not been attempted here.

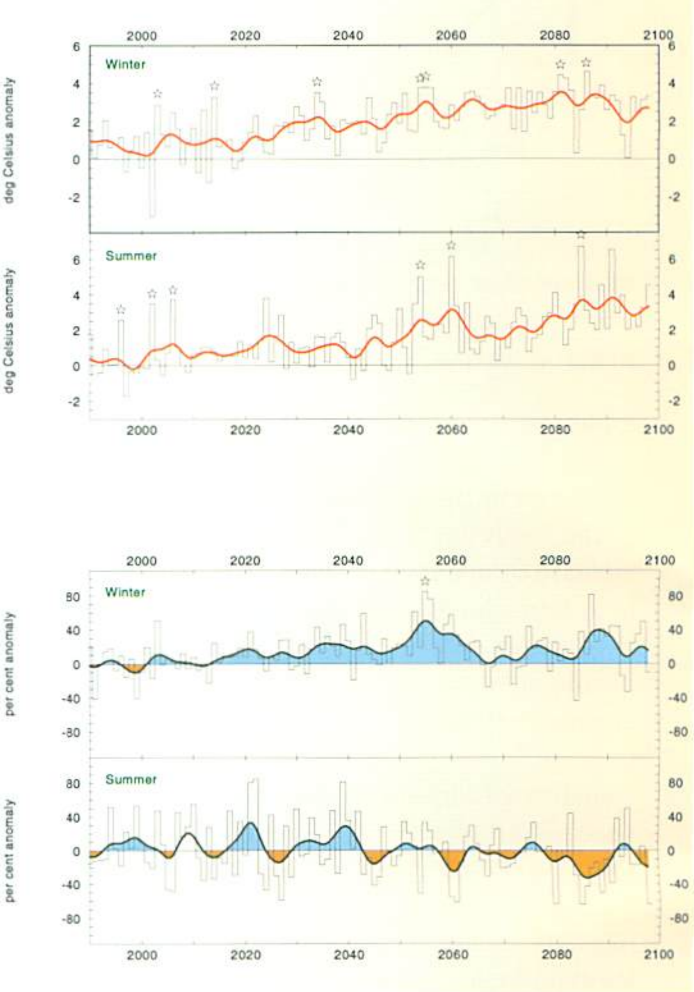


*Figure 33: One possible evolution of winter and summer mean temperature (top) and precipitation (bottom) from 1990 to 2099 for the southern UK (the average of two HadCM2 gridboxes) under the **Medium-high** scenario. Data are extracted from one member of the HadCM2 ensemble. Stars show the years in which new warm, dry or wet record seasonal anomalies are established according to this section of the model output. All data are shown with respect to modelled mean 1961-90 climate. Smooth curves emphasise variations on time-scales greater than 10 years.*

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12 *Note that these dates are illustrative only - we are not actually predicting, for example, a record warm summer in 2002*

The point of including this analysis, and the graphs shown in Figure 33, is to emphasise that even under the changes in average thirty-year climates shown in earlier maps, the year-by-year evolution of climate over the UK will have substantial variability. There may well be long periods in the future which show relatively little warming (e.g. the period '2007' to '2023' for summer temperature; Figure 33 top), or shorter periods which show precipitation trends opposite to those expected according to the thirty-year mean changes shown earlier (e.g. late 2050s to 2070 winter drying, or 2020s to 2040 summer wetting; Figure 33 bottom).

	Summer temperature (°C)		*Winter temperature (°C)*		*Summer precipitation*		*Winter precipitation*	
Current record	1976	+2.4	1868/69	+2.7	1995	-67%	1914/15	+68%
Model records	**1996**	**+2.6**	**2002/03**	**+2.9**	2005	-48%	2002/03	+50%
	2002	**+3.5**	**2013/14**	**+3.3**	2006	-50%	2042/43	+59%
	2006	**+3.7**	**2033/34**	**+3.5**	2027	-60%	2052/53	+61%
	2054	**+5.1**	**2053/54**	**+3.7**	2061	-62%	**2054/55**	**+88%**
	2060	**+6.2**	**2054/55**	**+3.8**	2080	-64%		
	2085	**+6.8**	**2080/81**	**+4.4**				
			2085/86	**+4.6**				

Table 10: Years in which record seasonal temperature and precipitation anomalies (warm seasons, dry summers, wet winters) are established according to the evolution of climate shown in Figure 33 for southern UK. Current records are taken from the Central England Temperature and England and Wales Precipitation series based on their full series length. All anomalies are with respect to mean 1961-90 climate. The anomalies shown in bold exceed the current observed records. Note: these years are illustrative only and should not be interpreted as predictions for specific years.

Chapter 6: Obtaining Regional Scenario Information

The climate scenario information for the UK provided thus far has been depicted at the spatial scale that is resolved by the HadCM2 climate model, namely 2.5° latitude by 3.75° longitude. This model resolves only four discrete regions within the UK - roughly describable as 'Scotland', the 'Scottish/English borders', 'Wales' and 'England' - and HadCM2 is one of the highest resolution coupled global climate models yet developed. Each of these four model gridboxes represents tens of thousands of square kilometers, within which there is a large amount of spatial variation in climate. For this reason the scenarios provided in this Report should be regarded mainly as national climate scenarios.

The coarse resolution of global climate models such as HadCM2 has a number of implications for the climate change scenarios derived from them. First, the coarse GCM-grid greatly simplifies the coastline and topography of a country like the UK. For example, the Shetland Islands do not exist in HadCM2 and the elevation throughout the 'Scotland' gridbox is 221 metres. These simplifications of geography may alter the larger-scale circulation in the model and make the modelled response to anthropogenic forcing - even at the GCM resolution - different from what it would realistically be. Second, within each gridbox there is a great deal of heterogeneity in the land cover characteristics that interact with the atmosphere. This heterogeneity cannot be captured by a GCM and, again, means that the large-scale modelled response to external forcing is greatly simplified. Third, and largely because of the first two limitations, within a single GCM gridbox there may in reality be quite different climate responses to anthropogenic forcing. Thus warming over the east of Scotland may be different to warming over the west. Our UKCIP98 scenarios cannot discriminate between such local differences.

This coarse spatial resolution of GCM-based scenarios is therefore at first sight a major limitation in their application to a wide range of impact assessments. These assessments may either be quite localised - around a single river catchment or urban area - or may operate on a national scale, but with a spatial resolution of kilometres or tens of kilometres rather than hundreds of kilometres - for example a national land use classification assessment. How can the scenario information portrayed in this Report be useful, or be made to be useful, in such impacts assessments? The answer to this question requires some consideration of the problem of 'downscaling' climate change information. We briefly summarise some of these options in this Chapter. A full downscaling analysis for the UK is beyond the scope of this Report, but may be dealt with in subsequent Reports in this series.

Global climate models cannot simulate the climate over complex mountain terrain such as found in North Wales (photo: Colin Brown)

Downscaling is also necessary for information regarding changing sea-levels. We showed one simple example in Figure 32 where we took a global-mean sea-level change and applied it to a local situation. More sophisticated downscaling efforts for sea-level changes would need to consider the interaction between any change in mean sea-level and shoreline erosion rates, the local tide-regimes, changes in storm regimes, bathymetry, etc.

6.1 Unintelligent Downscaling

One of the crudest ways of adding spatial detail to GCM-based climate change scenarios is to interpolate GCM-scale changes to a finer resolution and then combine these interpolated changes with observed climate information at the fine resolution. This may be achieved using high resolution observed mean monthly climatologies or can be done simply by perturbing an observed monthly or

daily time series for a site or catchment by the GCM changes interpolated to the site in question.
We have adopted the first approach on the CD-ROM that accompanies this Report. The various UKCIP98 scenario changes for different periods are interpolated to a 10 km resolution using a standard spatial filter and then added to the observed 10 km mean monthly climatology for 1961-90 to yield climatologies for the 2020s, 2050s and 2080s at the same resolution as the baseline climatology.

This approach is termed 'unintelligent' because we add no new meteorological insight that goes beyond the GCM-based changes into the interpolation procedure and we assume that the basic spatial pattern of present climate remains largely unchanged in the future. This very simple approach to downscaling is easy to apply and allows impact assessment models to use climate scenarios at a resolution that would otherwise be difficult or costly to obtain. Some other technical problems with this approach are summarised in Appendix 7.

6.2 Statistical Downscaling Methods

Because unintelligent downscaling assumes that climate change will be uniform over GCM grid-scales and because regional climate models are slow and expensive to run, another set of approaches to the downscaling problem has been developed for scenario applications. These approaches may conveniently be grouped together as statistical downscaling methods. There are at least three broad clusters of methods within this general category - regression methods, circulation typing schemes, and stochastic weather generators. We will say a few words about each in turn. It is worth noting, however, that developing a statistical downscaling model is usually quite time-intensive and will always require very extensive observational data - daily/hourly weather data, for the surface and maybe for the upper air, and usually for several/many sites or gridboxes covering the region of interest. It need not necessarily be a cheaper or easier option than running a regional climate model. It should also be noted that most downscaling methods and models are developed with a specific application in mind - whether agriculture, forestry, water, etc. - and quite often for a specific geographic region. Not all downscaling methods can easily be transported from one region to another. In each case, just as with a regional climate model, the derived regional scenarios depend completely on the validity of the GCM output.

6.2.1 Regression methods.

These approaches generally involve establishing relationships between large-scale (e.g. synoptic or gridbox scale climate) and small-scale (e.g. site) climate variables. These relationships are trained on observed data over some suitable period of time, before the resulting equations are 'driven' by large-scale climate output from a GCM experiment to derive the small-scale climate change scenario. Predictor variables typically include large-area average surface temperature and precipitation and upper air geopotential temperatures and heights.

6.2.2 Circulation typing.

Circulation-based downscaling methods usually involve relating site or small-scale climate data to a synoptic weather/circulation classification scheme. These classification schemes may be objectively or subjectively determined. One of the most widely used in UK downscaling studies is the Lamb synoptic classification. As with regression-based methods, once these relationships are determined from observed data, the relationship may be used with a daily classification series derived from a GCM experiment. One attraction of these circulation-based methods is that they are based on the well-established linkages between synoptic circulation and local weather statistics, such as the probability of a wet day. The credibility of regression methods and of circulation typing techniques depends upon the relationships established using observed data persisting in a changed climate. This assumption may well not be valid.

6.2.3 Stochastic weather generators.

Weather generators (WGs) are another way of constructing site specific or small-scale climate change scenarios, although they rely on a slightly different approach from other statistical downscaling methods. A weather generator is calibrated on an observed daily weather series over some appropriate period, usually for a site, but possibly for a catchment or a small gridbox.

The generator is then capable of generating, stochastically, an infinite series of daily weather for the respective spatial domain, this series possessing - in theory - the correct lower and higher order climate statistics for that domain. The parameters of the weather generator are then perturbed using output from a GCM allowing the generator to yield synthetic daily weather for the climate change scenario. To derive the appropriate WG parameter perturbation from the coarse-scale GCM, one of the above two downscaling methods may be employed. One of the weaknesses of weather generators is that because they are stochastically based, they do not always capture the low frequency (decade to decade) variations in climate that may be quite important for certain impacts applications. Appendix 8 provides links to one commonly used public-domain weather generator in the UK.

6.3 Dynamical Downscaling Methods

Another downscaling option is to use a higher resolution limited-area model (often called a Regional Climate Model - RCM) to generate climate change scenarios at the required resolution. Such regional climate models typically cover an area the size of Europe, have a spatial resolution of about 30-50 km and are driven by boundary conditions taken from the GCM. This approach has been adopted by a number of modelling centres around the world including the Hadley Centre. Figures 34 and 35 show the difference in the response of mean winter and summer temperature and precipitation over the UK when modelled by the HadCM2 global model with a resolution of 300km compared to the results from the Hadley Centre regional model with a resolution of 50 km. This analysis is for the **Medium-high** scenario, but for the twenty-year

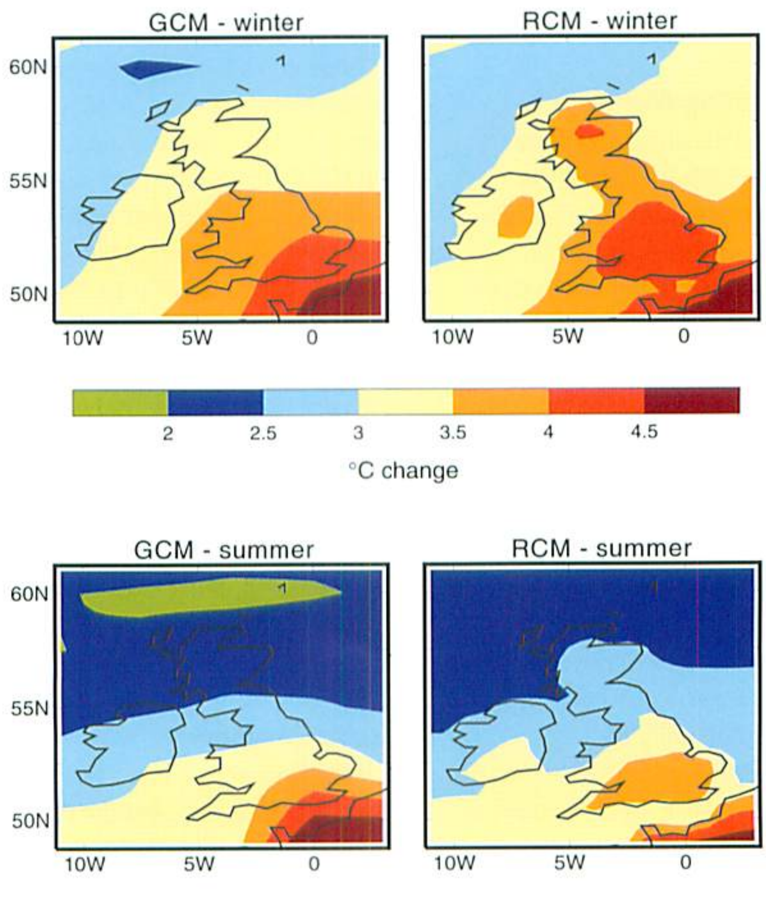

Figure 34: Change in mean winter (top) and summer (bottom) temperature (degC) over the British Isles for the period 2080-2100 relative to the control simulation for the HadCM2 GCM (left) and the Hadley Centre RCM (right). The forcing scenario is the GGa forcing scenario that forms the basis of the UKCIP98 ***Medium-high*** *scenario.*

period 2080-2100 (not quite the same as the 2080s period used earlier in this Report).

The broad patterns of response are similar between the two models with the temperature warming greatest in the southeast and least in the northwest (Figure 34) and with winter showing wetting everywhere and summer showing wetting in the north and drying in the south (Figure 35). It is also possible from these plots to see some of the influences of the higher resolution geography on the regional climate model results. Thus the effect of the English Channel can be seen in dampening the winter and summer warming rates in coastal regions and local heating over the Scottish mountains can be seen in winter. The regional model shows larger precipitation increases over the Scottish Western Isles than over the eastern lowlands of Scotland, a difference totally absent in the GCM output.

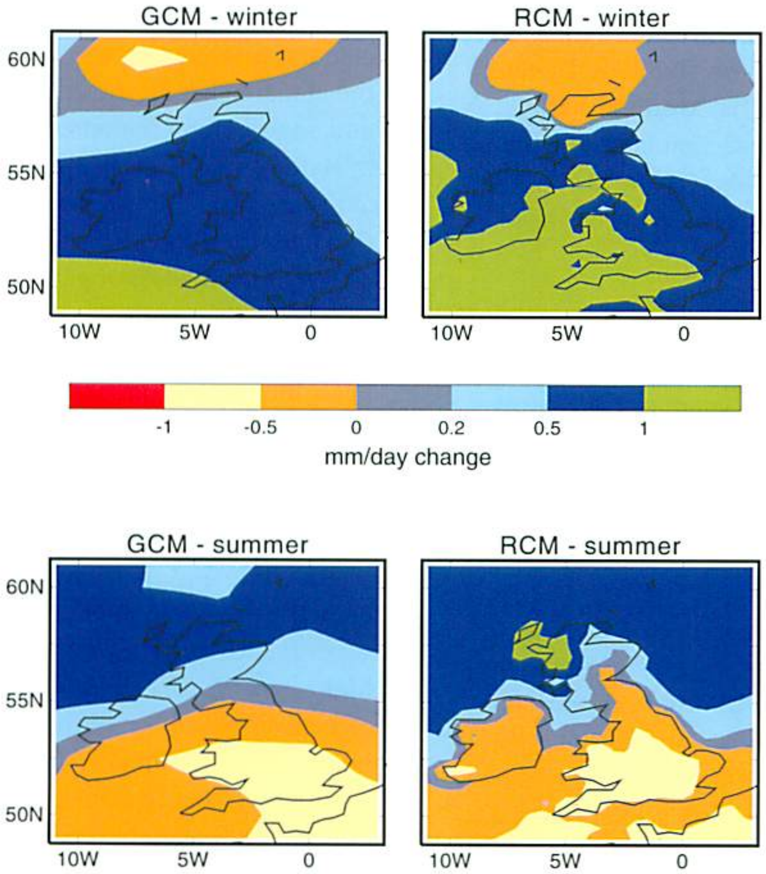

Figure 35: As Figure 34, but for precipitation change in mm/day.

Just because results from RCM experiments show greater spatial detail than GCMs, including the appearance of sensitivity to more realistic geography, does not automatically qualify them as more 'accurate'. There are several acknowledged limitations to the regional climate modelling approach. The most important of these is that the RCM is completely dependent upon the boundary conditions extracted from the GCM experiments to drive the regional atmosphere. The RCM scenario therefore depends greatly on the validity of its driving GCM. It is also worth noting that regional climate model output even at 50 km resolution is still not adequate for some impacts assessments. In cases such as a small river catchment or the simulation of agriculture or land use at 1 km or 10 km scales there will still be a need for some other form of downscaling, even of regional model output. RCMs also require considerable computing resources and are as expensive to run as a global climate model. Nevertheless, RCMs hold much promise for providing high resolution climate scenarios at the regional scale. Some results from the Hadley Centre regional climate model for Europe are available from the Climate Impacts LINK Project (see Appendix 8).

Chapter 7: The UKCIP98 Scenarios in Wider Context

7.1 Results from other Climate Models

We have based the UKCIP98 climate scenarios on results from the HadCM2 climate model experiments. A further context in which to evaluate these scenarios is provided by results from a number of other recently completed coupled ocean-atmosphere global climate model experiments. There are many climate laboratories around the world that perform similar climate experiments to the Hadley Centre experiments used here. We have therefore compared the changes for the **Medium-high** UKCIP98 scenario with those simulated by three other leading climate models (Figure 12 showed the global warming curves resulting from these experiments):

- the Max Planck Institute for Meteorology model at Hamburg (ECHAM4)
- the Geophysical Fluid Dynamics Laboratory model at Princeton in the USA (GFDL-R15)
- the Canadian Climate Centre for Modelling and Analysis model at Victoria, British Columbia (CGCM1).

Results from experiments performed by these three other leading climate modelling centres have all been lodged with the IPCC Data Distribution Centre (see Appendix 5), experiments that have used essentially the same anthropogenic forcing scenario as in the **Medium-high** scenario and a similar experimental design. Differences between these four sets of experiments therefore occur because of different model designs and parameterisations - which result in different climate sensitivities - rather than because of different forcing scenarios or experimental design.

Figures 36 and 37 show changes in mean annual temperature and precipitation for three time periods for these other models, alongside the **Medium-high** UKCIP98 scenario derived from HadCM2 (*cf.* Figures 13 and 16). The other three models all show more rapid annual warming over the UK compared to the **Medium-high** scenario, by almost 1°C in the case of ECHAM4.

For precipitation, all models show an increase in annual precipitation over northern UK, but differ in their response in the south. ECHAM4 shows a strong pattern of drying over southern England, while GFDL-R15 shows slight drying annually over the southwest. These differences between models are further summarised for winter and summer in Figure 40.

7.2 The Effects of Natural Climate Variability

We have mentioned the importance of natural climate variability in previous chapters. Some of the climate change shown in the UKCIP98 scenarios and analysed in Chapters 4 and 5 will be caused by natural variations in climate rather than by anthropogenic forcing of the climate system. Given that the UKCIP98 climate scenarios are to be widely used in assessments of anthropogenic climate change impacts, and of possible adaptation strategies to anthropogenic climate change, it is important that we give some consideration to separating these two effects. We can use the HadCM2 series of experiments to help us.

First, we examine the differences in the temperature and precipitation changes that exist between the ensemble members[13] of the HadCM2 experiments which form the basis of the **Medium-high** scenario. These intra-ensemble differences give us an indication of the relative contributions of human-induced climate change and natural climate variability to the climate changes shown in this Report. Little variation between ensemble members would suggest that most of the change is human in origin; large variations between the members suggest a larger role for natural climate variability. Second, we show some results from an analysis of the 1,400 year control simulation of global climate made with HadCM2. This simulation generates a large sample of possible climates that result from natural climate variability alone. We can compare these natural changes in UK climate with those extracted from the various climate change experiments we have used to create the UKCIP98 scenarios.

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13 *See Appendix 2 for further explanation about ensemble experiments*

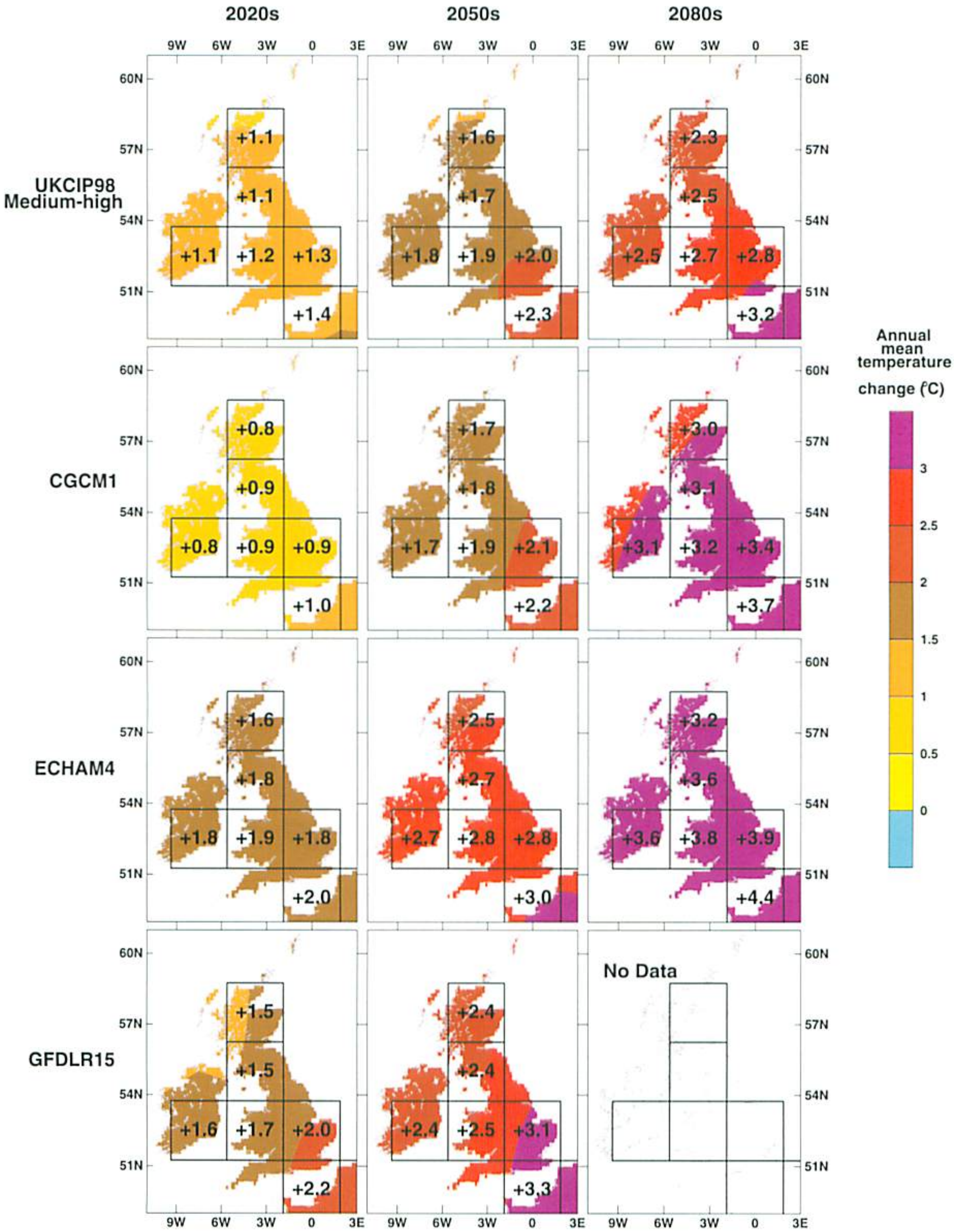

Figure 36: Change in mean annual temperature (wrt 1961-90) for thirty-year periods centred on the 2020s, 2050s and 2080s for the four climate models presently included in the IPCC Data Distribution Centre. The background fields are interpolated from the respective full model grids, while the plotted numbers show the respective change for each HadCM2 land gridbox over the UK. ECHAM4, GFDL-R15 and CGCM1 grids are interpolated onto the HadCM2 grid for this purpose. These results all equate to the UKCIP98 ***Medium-high*** *scenario. Note: the GFDL-R15 experiment does not extend to the 2080s.*

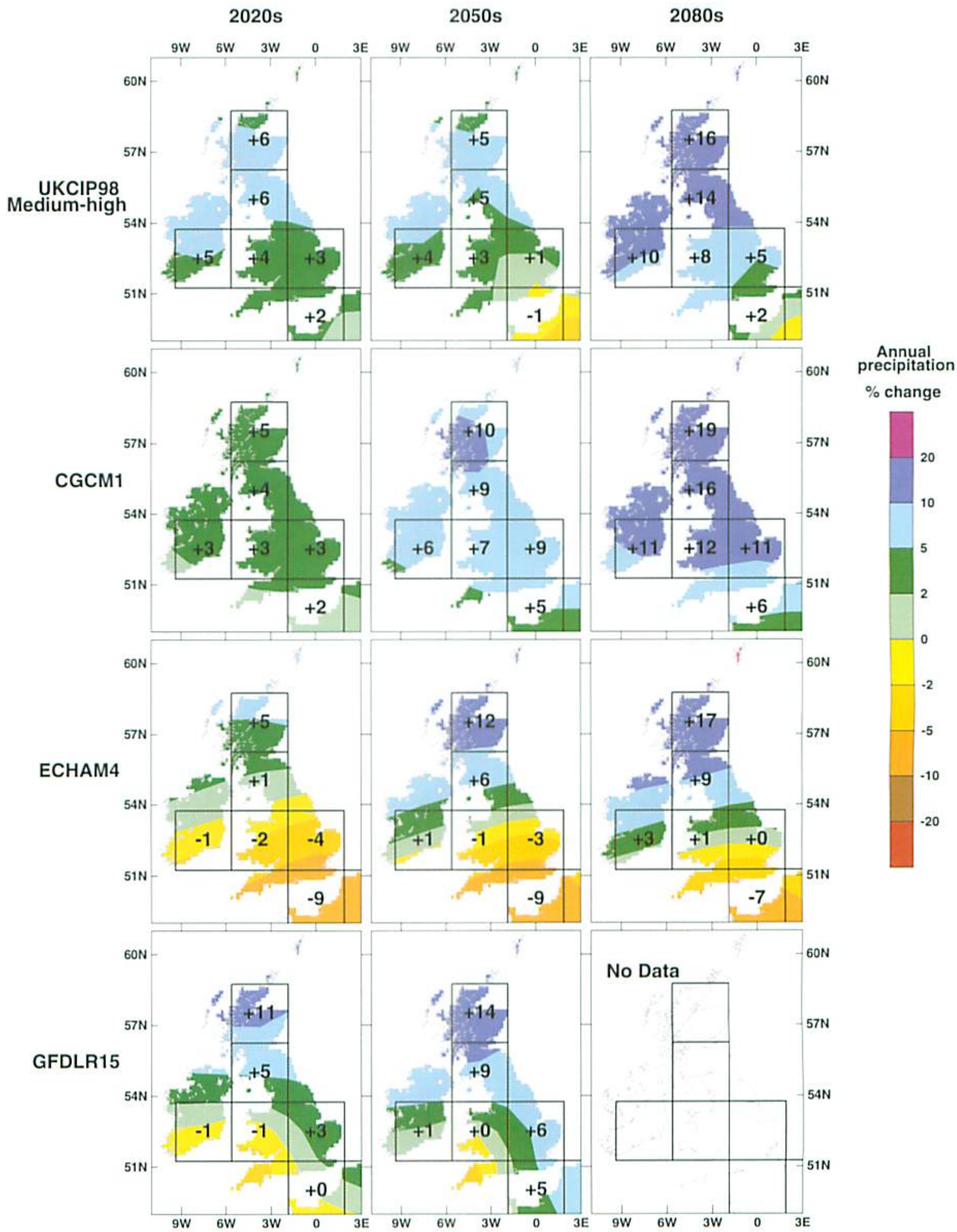

Figure 37: As Figure 36,but for annual precipitation change.

Note that in all of these analyses we are analysing multi-decadal (thirty-year mean) climate variability resulting from internal ocean-atmosphere variability, not the additional increment of natural variability that changes in solar or volcanic forcing of the climate system would induce. These analyses therefore probably underestimate slightly the real world natural variability. Also, it should be noted that these are estimates of natural variability derived from one climate model - HadCM2 - and not from observations.

7.2.1 *Intra-ensemble differences.*

Figures 38 and 39 show the mean seasonal and annual changes in, respectively, mean temperature and precipitation for the ensemble-mean of the HadCM2 experiment used to create the **Medium-high** scenario. These are the same changes as shown in Figures 16, 17 and 18 in Chapter 4. Superimposed on these plots, however, we now show the range of these quantities as defined by the four individual ensemble members of this experiment. These numbers therefore define a range of thirty-year mean climate changes that could actually be experienced for the respective periods after allowing for the contribution that natural climate variability may make. Another way of interpreting Figures 38 and 39 is that the ensemble-mean changes show the 'expected' human- induced climate change signal, while the ensemble range shows the effects of combining this anthropogenic signal with the effects of natural climate variability as defined by the model. All of the changes shown within the ensemble range are entirely consistent with the **Medium-high** scenario we have previously presented.

For the temperature changes (Figure 38), the intra-ensemble range varies from about ±20 per cent of the ensemble-mean change in the 2020s to less than ±10 per cent by the 2080s. In other words, the **Medium-high** seasonal temperature changes are due largely to human-induced climate change rather than to natural climate variability. For example, annual warming over eastern England by the 2080s is +2.8°C as an ensemble-mean, but any single realisation of climate change by this period may lie between +2.6° and +3°C. For precipitation changes however (Figure 39), the situation is rather different. In certain seasons and for some periods, the intra-ensemble range matches or even exceeds the ensemble-mean change suggesting that a large proportion of the seasonal-mean precipitation changes in the **Medium-high** scenario is due to natural climate variability rather than being due to human-induced climate change. This is especially true for the 2020s period, but is also largely true for spring even by the 2050s and the 2080s. Thus, for example, precipitation change in spring over Wales by the 2080s is +4 per cent as an ensemble-mean, but any single realisation of climate may yield seasonal changes between +15 per cent and -2 per cent.

This analysis of ensemble variability has at least two important implications for using scenario changes in precipitation at this regional level. First, ensemble-mean changes should be used in preference to changes extracted from single realisations if one is wishing to identify the human-induced component of future changes in mean climate. Second, even when using ensemble-mean changes, a better appreciation of the full range of multi-decadal natural climate variability is warranted before interpreting the results of such impacts assessments. Failure to appreciate the relative magnitudes involved may cause us to attribute the effects on social or environmental indicators of both human-induced climate change and natural climate variability as if they were the effects of human-induced climate change alone.

7.2.2 *Defining natural climate variability.*

The four-member ensemble from the HadCM2 experiments provides us with one estimate of uncertainty in our scenarios, an uncertainty that relates to the relative effects of human-induced climate change and natural climate variability. We also examine the 1,400 year control simulation of global climate made with the HadCM2 model to determine the range of natural climate variability for the UK from a larger sample of thirty-year climates. In this simulation, no changes in greenhouse gas concentrations or other climate agents were introduced, hence the changes occur purely because of natural effects within the ocean-atmosphere system. We divided this 1,400 period into thirty-year periods and then analysed by how much these thirty-year mean climates vary. Average temperature in the UK varies by about

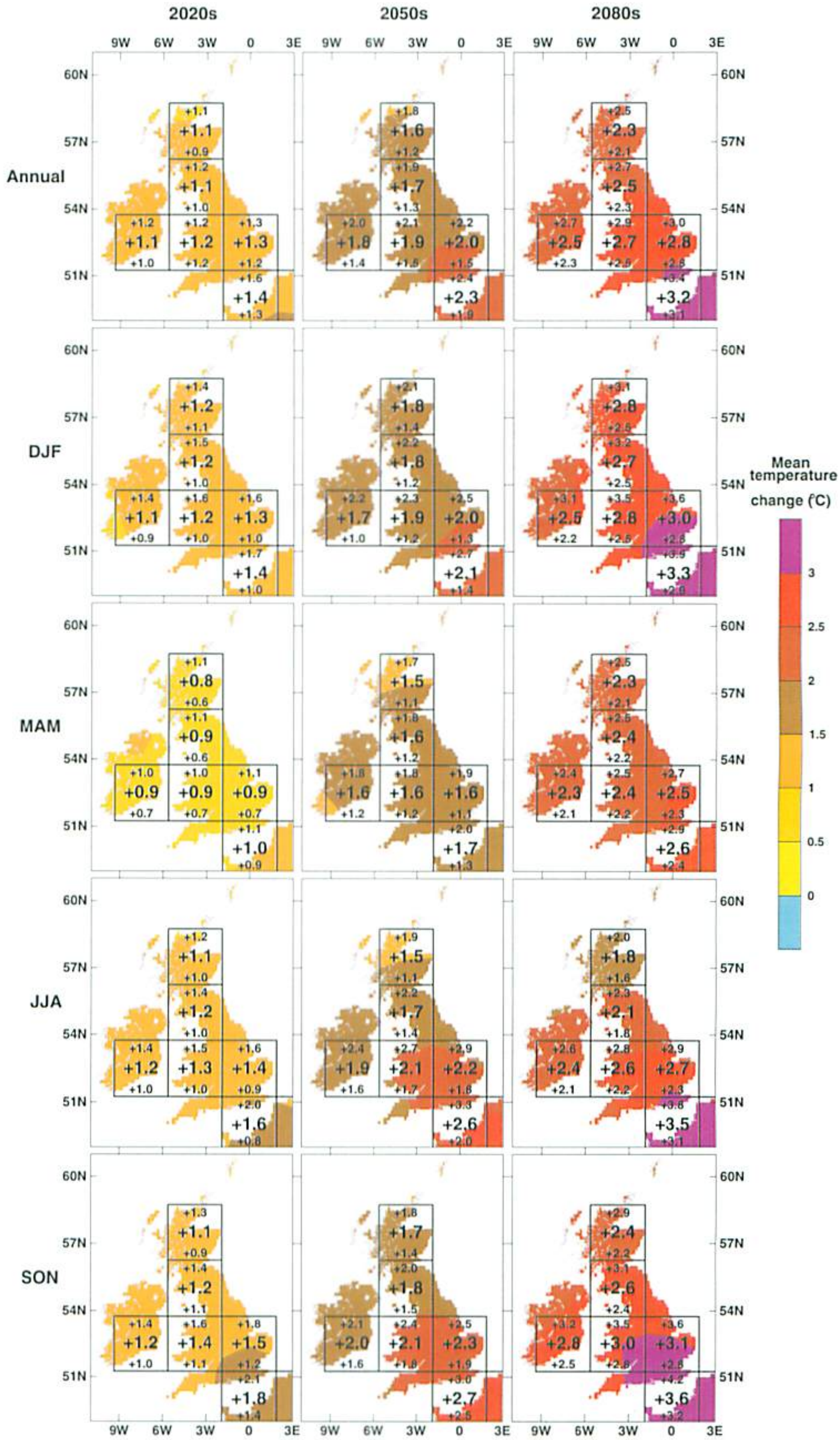

*Figure 38: Changes in mean annual and seasonal temperature (wrt 1961-90) for thirty-year periods centred on the 2020s, 2050s and 2080s (**Medium-high** scenario). Mean changes are derived from the ensemble-mean of the respective HadCM2 experiments - large bold numbers and background field - while the range is obtained from the four ensemble members of the experiment - small bold numbers. The background field is interpolated from the full HadCM2 grid, while the numbers show the respective change for each HadCM2 land gridbox over the UK.*

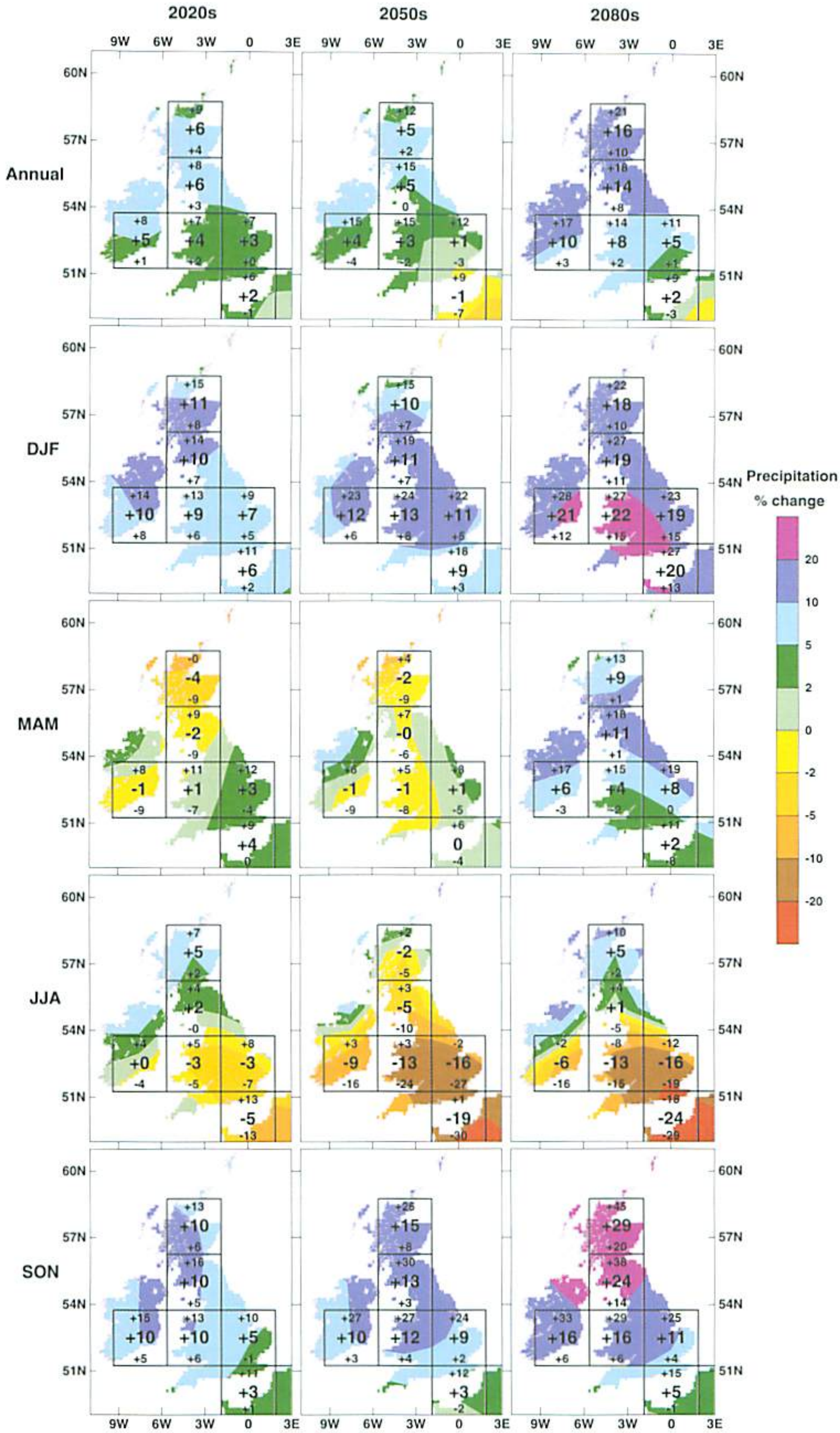

Figure 39: As Figure 38 but for mean precipitation change in per cent.

±0.6°C in winter and by about ±0.4°C in summer, while average precipitation varies by about ±10 per cent in both summer and winter.

7.3 Combining Sources of Uncertainty

Having examined in the previous sections differences in simulated climate change for the UK between different climate models, the uncertainties introduced by ensemble experiments, and the magnitude of natural climate variability, we combine these different types of information in Figure 40.

First, we plot the ranges of natural climate change for winter and summer as ellipses centred on zero in each of the graphs. These ranges tell us by how much the thirty-year climate centred on the 2050s - or any other thirty-year period - may differ from today without any human influence on climate at all. Next, Figure 40 shows the results for the four ensembles that comprise the **Medium-high** scenario. These are shown as red crosses in these plots, while the red squares indicate the ensemble-mean. The temperature changes between the ensemble members vary by up to 1°C or more in winter or summer, while the precipitation changes vary by more than 10 per cent. Indeed, in summer for the 2050s, one ensemble member simulates an increase in precipitation while the other three simulate decreases. Finally, we also plot the changes in UK climate for these periods as defined by the three other leading global climate models used by the IPCC. The blue, green and orange symbols on these graphs show a broad similarity with the seasonal temperature and precipitation changes defined by the **Medium-high** scenario, more so in winter than in summer. Winter precipitation, for example, increases in each model, while the changes in summer precipitation are much more variable. By the 2080s, the CGCM1 model depicts a 17 per cent increase in precipitation, while ECHAM4 shows a 20 per cent decrease. Such differences support our earlier conclusion that summer precipitation changes in the UKCIP98 scenarios should be cautiously interpreted.

7.4 Possible Rapid Climate Change

The UKCIP98 climate scenarios have been derived from climate models that include the best possible representation, consistent with current understanding and computing limitations, of processes in the atmosphere, ocean and land that will determine climate change. However, we do not understand the climate system well enough to be able to rule out other outcomes. It has been suggested, for example, that relatively rapid climate change could occur if the climate system shows a non-linear response to increased greenhouse gas concentrations.

The most likely example of this is a change in the thermohaline circulation (THC) of the world's oceans. The THC consists of strong ocean currents that transport large amounts of heat around the world. It has been suggested for some time that a collapse of the THC in the North Atlantic could cause cooling over northwest Europe. The THC brings warm sub-tropical water into the North Atlantic and this water loses its heat to the atmosphere, hence keeping northwest Europe, and particularly the British Isles, warmer than they would otherwise be. It is thought that under certain climate regimes the THC could flip from an 'on' state to the colder 'off' state. The last time this is believed to have happened in a major way was in the Younger Dryas era, about 11,000 years ago, when Europe experienced a substantial cooling for a few centuries, interrupting the general warming coming out of the last ice age. There is also some suggestion that weaker variations in the THC have occurred more recently, resulting in less dramatic, but still significant, climate variability on a number of different time-scales.

Climate models show that increased greenhouse gas concentrations are likely to produce an increased input of fresh water into the North Atlantic in the form of precipitation and a reduced heat loss from the surface of the ocean to the less-cold north Atlantic winds. Both these effects would tend to suppress the formation of dense water at high latitudes, which is the main driving

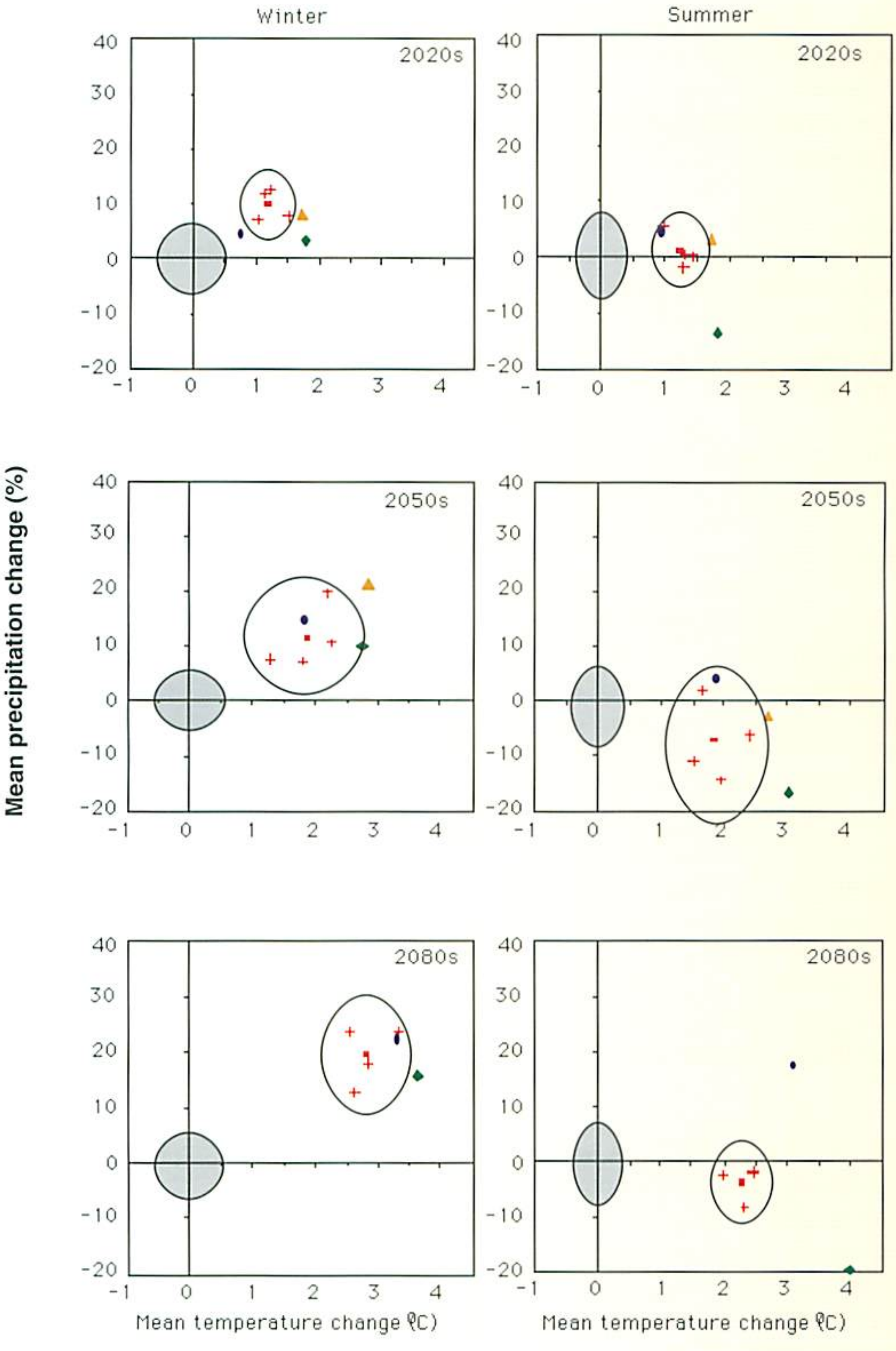

Figure 40: Changes in mean winter (left) and summer (right) temperature and precipitation over the UK (average of the four HadCM2 land gridboxes) with respect to 1961-90 mean climate. Shaded ellipses centred on the origin are the 2σ limits for thirty-year mean UK climates derived from the HadCM2 control simulation. The symbols show changes in thirty-year climate averages centred on the respective decades. The red symbols are for the UKCIP98 ***Medium-high*** *scenario and the blue, green and orange symbols are for the other models used by the IPCC - CGCM1, ECHAM4 and GFDL-R15. These changes may be compared with those shown in Figures 36 and 37. The ellipses centred on the UKCIP98* ***Medium-high*** *scenario are the 2σ limits derived from the four ensemble members of the respective HadCM2 experiment. Note: the GFDL-R15 experiment does not extend to the 2080s.*

force for the THC. Under these conditions the THC would weaken. There is also good reason to believe that, as the freshwater input increases, the system becomes more prone to a sudden flip to the 'off' state. Such flips could conceivably happen on a time-scale of 20-50 years.

The Hadley Centre model, in common with some others, shows a slow weakening of the THC as greenhouse gas concentrations increase. It is important to realise, however, that the slow cooling due to this effect will only partially offset the general warming from the increases in greenhouse gases. The North Atlantic will still warm, but parts will warm at a slower rate than if the THC had remained constant.

A sudden, more dramatic collapse of the THC has not been seen in any experiment using the most comprehensive climate models. Nevertheless, we must take the possibility seriously because of the potential major impact of such an event. Large unforced variations in the THC have been seen in some climate models, albeit less dramatic than those assumed to have occurred earlier in the Holocene, but which still lead to significant climate impacts on the UK. There are also some model studies that suggest that THC variability becomes larger as a result of global warming. The Hadley Centre is currently actively working to improve our understanding of the climate system and to identify as early as possible any mechanisms that might lead to rapid, non-linear, climate change.

Another area for concern lies in the behaviour of the West Antarctic Ice Sheet (WAIS). It is possible that a much more rapid rise in sea-level than suggested in our scenarios could occur should the WAIS begin to disintegrate. The WAIS is grounded below sea-level and is therefore potentially unstable. If it were to disintegrate completely, global sea-level would rise by about five metres. Predictions about the contribution of the WAIS to sea-level rise are difficult and uncertain for at least two reasons. First, is the complexity of processes determining the stability of the WAIS and, second, is the uncertain relationship between changes in accumulation and discharge of ice due to global warming and the effects of natural millenial-scale trends in climate. The most likely scenario appears to be one in which the WAIS contributes relatively little to sea-level rise in the twentieth century, but over following centuries higher discharge rates from the ice sheet increase its contribution to sea-level rise to between 50 and 100 cm per century. It is important to note, however, that the rapidity of the WAIS disintegration may depend upon warming over the next century, which in turn is already being determined by current emissions of greenhouse gases.

The contribution of changes in Antarctic ice sheets to global sea-level is uncertain. A disintegration of the West Antarctic Ice Sheet could greatly accelerate the rise in average sea-level. [Photo: Karen Heywood].

Chapter 8: Further Scenario Characteristics

8.1 Uncertainties and Levels of Confidence

The future climates of the UK illustrated in this Report are scenarios. They are plausible and self-consistent descriptions of future UK climate based on different assumptions about future emissions of greenhouse gases. The transformation of these emissions into future climate change estimates is itself beset with uncertainty due to the role of other climate agents and poorly represented processes in the climate models. The range of uncertainty in global-mean temperature due to this aspect is conventionally taken to be about +50 per cent to -30 per cent around the modelled estimate, although work is in hand to derive better, statistically-based, estimates of this uncertainty range.

Other factors that are not predictable will almost certainly affect climate, in particular cooling due to volcanic dust and both warming and cooling due to the changing energy output of the sun. However, the climate effect of even a major volcanic eruption such as Mt. Pinatubo in 1991 disappears after a few years and so, barring an unusual succession of major energetic eruptions, modifications of the climate change scenarios shown here due to volcanoes are likely to be small. Although the direct output of the sun affects climate, this effect has been small over the past 100 years and there are no indications that these quite modest effects will change in the future. There are theories that the sun can affect climate in indirect ways, such as its ability to modify cosmic rays and potentially cloud cover, but these theories remain speculative. Lastly, there is the possibility that we may be ignorant of other effects or feedbacks on climate that could lead to much greater, or much smaller, changes in future climate than shown here. Similar so-called 'surprises' have become apparent in other fields, for example the causes of the stratospheric ozone hole. By definition, the risk associated with surprises cannot be quantified.

The existence of uncertainties does not imply the absence of knowledge. There are some aspects of future climate change we may have greater confidence in than others. Table 11 lists a number of the variables shown in this Report, ranked in descending order of confidence. This list is a matter of judgement and objective levels of confidence cannot be applied. Nevertheless, they indicate that we are more confident about increases in carbon dioxide concentrations and sea-level than we are about increases in storminess or intense precipitation. The likelihood of sudden, non-linear changes in regional climate is either very low or simply unknown. Such a relative evaluation of confidence may be useful in an impact assessment when trying to interpret the effects of different sources of uncertainty on the range of impact indicator outcomes.

Climate Variable	
Atmospheric CO_2 concentration	***High confidence***
Global-mean sea-level	
Global-mean temperature	
Regional seasonal temperature	
Regional temperature extremes	
Regional seasonal precipitation	
Regional cloud cover	
Regional potential evapotranspiration	↓
Changes in climatic variability e.g. daily precipitation regimes	***Low confidence***
Climate surprises (e.g. THC collapse and WAIS disintegration)	***Very low or unknown***

Table 11: List of climate and associated variables, ranked subjectively by the authors in decreasing order of confidence. This ranking assumes a specific emissions scenario (and therefore does not consider uncertainties resulting from an unknown emissions future). 'Regional' means the pattern of change across a country like the UK.

8.2 The Choice of Scenarios

It is not possible to quantify the relative probabilities of each of the four UKCIP98 scenarios occurring. The difference between the **High/Medium-high** and **Medium-low/Low** scenarios relates to different levels of future greenhouse gas concentrations. The 1 per cent per annum growth in concentration upon which the **High/Medium-high** scenarios are based, approximates the IS92a emissions scenario which

has been widely used as a standard emissions profile. The **Medium-low/Low** scenarios are based on a concentration growth of about 0.5 per cent per annum and therefore reflect an emissions profile more like IS92d than IS92a. All of the IS92 emissions scenarios were non-intervention scenarios and were based on different assumptions of population and economic growth and on different energy futures. The new set of emissions scenarios being prepared for the IPCC (the SRES98 scenarios; see Appendix 3) are also all non-intervention scenarios and the range of their greenhouse gas forcing profiles ranges from about 0.4 per cent per annum growth to about 1.3 per cent per annum. Whether or not one sees these emissions profiles as equally likely, it is quite clear that our **Medium-high** and **Medium-low** scenarios span a reasonable part of range of the possible future climate outcomes that is due to different anthropogenic forcing.

The difference between the **High, Medium-high/Medium-low** and **Low** UKCIP98 scenarios stems from the sensitivity of the climate system to changing concentrations of greenhouse gases. The **High** scenario assumes the highest likely sensitivity and the **Low** scenario the lowest likely sensitivity. The **Medium-high** and **Medium-low** scenarios both use the climate sensitivity of the HadCM2 model which falls someway between the two extremes.

The outcome of an impact assessment will depend to a significant extent on the climate change scenario that is chosen. Since we cannot attach probabilities to the different emission profiles and climate sensitivities that create the UKCIP98 scenarios, the full range of scenarios should ideally be evaluated to identify the potential risks of climate change and the effectiveness of different adaptive strategies. Where only a single scenario is used, say the **Medium-high** scenario, caution should be exercised when interpreting the results of the assessment.

8.3 Future Modelling and Scenario Developments

8.3.1 HadCM3 results

Since compiling this report, the third version of the Hadley Centre climate model, HadCM3, has been developed. Many of the representations of processes in the atmosphere, in the ocean and on land, have been improved and the ocean resolution in the new model is more than doubled. This gives the model a much better representation of ocean currents such as the Gulf Stream. Climate models have always relied on artificial corrections, known as flux-adjustments, to prevent their simulated climate from drifting away from reality. Improvements to the components of HadCM3 have enabled the model to run without resorting to the use of flux-adjustments and yet still achieve a good simulation of current climate with little drift in climate.

To date, only a single simulation has been made with HadCM3 using one of the IPCC 'non-intervention' emissions scenarios (IS92a) to determine the concentration and radiative forcing of each of the greenhouse gases separately. The broad-scale global climate changes simulated by HadCM3 are similar to those used in the UKCIP98 scenarios. There are some differences, however, over the UK as seen in Figure 41. The reduction in summer precipitation is greater than that seen in the **Medium-high** scenario and the increases in average wind speed are significantly greater than the small changes simulated by HadCM2. However, we are here comparing a single experiment using HadCM3 with the ensemble-mean of four experiments made using HadCM2; further experiments with HadCM3 may not show such clear differences. Future reports from UKCIP will assess the significance for the climate scenarios described here of new HadCM3 experiments.

Different climate change scenarios will lead to different impacts on the UK landscape. And different impacts will trigger different adaptations to climate change.

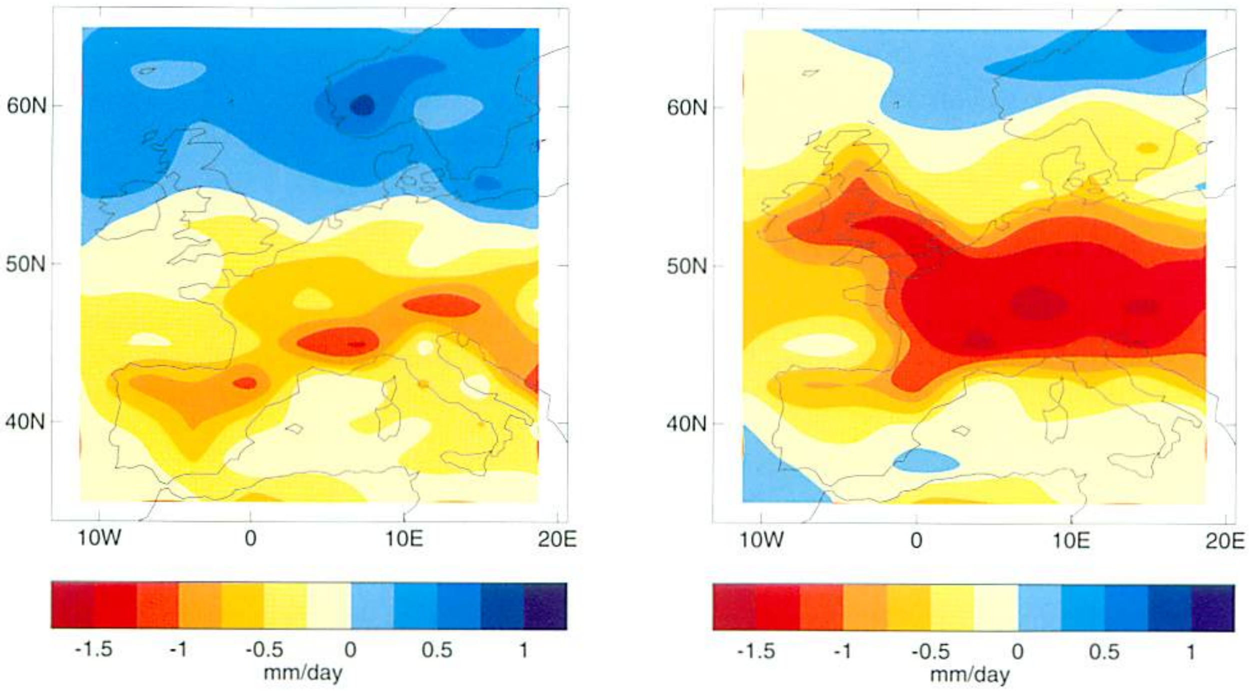

Figure 41: Mean summer precipitation change by the 2080s from (left) the UKCIP98 ***Medium-high*** *scenario (cf. Figure 18) and (right) the first HadCM3 simulation. Changes are mm/day with respect to the model-simulated 1961-90 climate.*

8.3.2 Medium-term climate variability and its prediction.

Even in the absence of any human perturbation of the climate system, climatic conditions vary from year-to-year and from decade-to-decade, for entirely natural reasons. This variability is caused by internal fluctuations in the climate system, mainly due to the interaction between ocean and atmosphere, and also by external forcing agents. Two examples of external agents are changes in the energy output from the sun and changes in the amount of volcanic 'dust' in the stratosphere. Climate models simulate, to a greater or lesser extent, the internal variability of the climate system. Consequently, to ensure that climate change scenarios are representing real human-induced climate change rather than the effects of natural climate variability, model results are usually averaged over a long period, in our case over thirty years, and where possible for an ensemble of simulations.

Until recently, it was thought that the variability of the climate system over a period of 1-10 years (known as 'decadal variability') was random and unpredictable. However, recent research has shown the potential for predictability over this time period. Analysis of observations of sea surface temperatures have identified modes in the ocean which retain their identity for a decade or more while they are transported, for example, from the east coast of America to Scotland. If these modes can be adequately simulated in climate models, then they may be predictable. Furthermore, changes in sea surface temperatures do appear to be significant drivers of UK climate, such as the warmth or wetness of winters.

If further research demonstrates that broad changes in climate, such as the run of warm winters in the late 1980s/early 1990s, are predictable in this sense, then the availability of this sort of forecast could be of considerable benefit to industry and commerce, not only in its own right, but also as an aid to planning for larger changes in the future due to human-induced global warming. For example, it would be useful for a water company to know that, despite a scenario of reduced precipitation over southern UK in the middle of next century, three or four years in the middle of the decade of the 2010s might actually experience greater than average amounts of precipitation. Research at the Hadley Centre and at UK universities is aimed at demonstrating this potential and realising it on an operational basis, although several more years work will be needed to reach this goal.

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Appendix 1: The CCIRG91, CCIRG96 and UKCIP98 Scenarios

Climate change scenarios for the UK were prepared for the Department of the Environment in 1991 and again in 1996. These were part of the Climate Change Impacts Review Group (CCIRG) reports published by HMSO in these years. The UKCIP98 scenarios differ from these earlier descriptions both in the way they are presented and also in some matters of substance.

Both the CCIRG91 and CCIRG96 scenarios tended to present a 'best guess' scenario for the UK derived from, respectively, five equilibrium GCM experiments completed in the late 1980s and from one transient GCM experiment - the UKTR (HadCM1) transient experiment - completed in 1992. Although both of these earlier scenarios presented a range of scenarios at the global-scale, and also some range of results at the UK scale, in UKCIP98 we provide a more explicit quantification for the UK of four alternative climate change scenarios. We also present analysis in UKCIP98 for a wider range of variables and on a wider range of time-scales.

The global-mean temperature change of the UKCIP98 scenario range is broadly similar to that used in the CCIRG91 report, but the patterns of change over the UK are quite different from CCIRG91 and partly different from those in CCIRG96. The summary differences are as follows:

- The CCIRG96 global-mean temperature change was slightly higher than the UKCIP98 **Medium-low** scenario.
- The CCIRG96 global-mean sea-level rise was between the UKCIP98 **Medium-high** and **High** scenarios.
- The UK temperature change in CCIRG96 fell between the UKCIP98 **Medium-high** and **Medium-low** scenarios, but CCIRG96 possessed a stronger northwest-to-southeast contrast in winter temperature than the UKCIP98 scenarios. The patterns of temperature change in CCIRG91 were very different from both CCIRG96 and UKCIP98.
- The UK pattern of precipitation change in CCIRG96 was broadly similar to UKCIP98, but there is a more uniform UK winter wetting in UKCIP98 than in CCIRG96. The magnitudes of these different scenarios are difficult to compare because in all cases the anthropogenic component of the seasonal precipitation changes is recognised as being weakly defined.
- The UKCIP98 changes in potential evapotranspiration are generally much lower than in CCIRG96, but with similar southeast-to-northwest gradients.
- The UKCIP98 changes in windiness - both mean seasonal winds and daily return periods - are generally lower than those in CCIRG96. This variable is again recognised as being poorly defined and the latest HadCM3 results suggests larger windspeed increases than in UKCIP98.

Appendix 2: The HadCM2 Model and Experiments

Climate Models

The HadCM2 climate model has been developed, in parallel with weather forecasting models, over a number of decades into a sophisticated tool for climate calculations. It is based on the known laws of physics describing the motion of energy and moisture and these equations are solved at intervals (typically 30 minutes) at a number of points forming a grid over the globe. In the HadCM2 model this grid is 2.5° in latitude by 3.75° in longitude; this corresponds to about 300 km by 350 km over the UK. Most processes in the atmosphere, ocean and on land which determine climate (cloud formation and development, for example) take place at scales much smaller than this and hence have to be represented ('parameterised') using larger-scale variables from the model.

A climate model has to include the ocean as well as the atmosphere - not just the continuous transfer of heat, water and momentum across the interface, but the ocean currents that transport vast amounts of heat between equator and poles. Only in the last few years have atmospheric models been successfully coupled to deep ocean models to allow the transient increase in climate to be properly modelled. Because components of the climate system can only be approximate representations of the real world, when they are coupled together the simulated climate tends to drift away from reality. This is prevented by imposing artificial corrections (known as flux-adjustments). Research indicates, however, that these adjustments do not invalidate results from the model used in this Report.

Predicting climate change due to an increase in greenhouse gases would be much more straightforward were it not for the consequential effects which follow an initial warming and which can act to either amplify or reduce it - these are known as feedbacks. The melting of sea-ice, for example, will reduce the amount of sunlight reflected and thus enhance the warming in high latitudes - a positive feedback. A warmer atmosphere will 'hold' more water vapour (a powerful greenhouse gas) and this too will act as a positive feedback. The greatest uncertainty in model predictions comes from these feedbacks and in particular possible changes in the behaviour and characteristics of clouds in a warmer world; we do not even know if this feedback will be positive or negative.

Stages in climate predictions

Predicting climate in the future is a multi-stage process. First, scenarios are created of future anthropogenic emissions of the greenhouse gases. These come from models that take account of such factors as growth in population, energy demand and technological change. In 1992, the IPCC issued a number of emissions scenarios, including a widely used scenario known as IS92a. In IS92a, carbon dioxide emissions increased from the current 7-8 GtC to about 20 GtC by the end of the next century, with similar growth in other greenhouse gas emissions (see Appendix 3).

Second, anthropogenic carbon dioxide emissions are translated into atmospheric concentrations using carbon cycle models. The natural carbon cycle involves the transfer of vast amounts of carbon between the atmosphere, the terrestrial biosphere and the oceans; the latter is by far the largest reservoir. Although carbon dioxide emissions due to human activities are only a small fraction of the natural cycle, they have led to a 30 per cent increase in carbon dioxide concentrations since pre-industrial times. Carbon cycle models estimate the amount of anthropogenic emissions that will be taken up by the ocean and the land biosphere and hence the amount retained in the atmosphere. The atmospheric concentration of carbon dioxide responds only very slowly to changes in emissions, unlike some gases whose concentrations respond roughly proportionately to changes in emissions. Only emissions reductions greater than about 60 per cent would prevent carbon dioxide concentrations from rising in the future (such a large reduction would be needed because past emissions have not yet been fully reflected in current concentrations). For other greenhouse gases, such as methane, future concentrations are calculated using models that represent chemical reactions in the atmosphere.

Finally, climate changes are investigated using the climate model described above. The model is run for many hundreds of (simulated) years to provide a control climate unperturbed by any external influences. Starting from an arbitrary point on the control run, the model is then forced with increases in greenhouse gas concentrations. The starting point is taken to represent the middle of the nineteenth century when any human influences would have been negligible (specifically the year 1860 was chosen as the start year to allow comparisons with global temperature observations). Over the period from 1860 to 1995 observed changes in greenhouse gases are used to simulate changes in climate to date. From 1995, a number of scenarios of future changes in greenhouse gases are used.

Climate change

Because most climate models are only able to handle carbon dioxide instead of the full range of greenhouse gases, it has become standard practice to drive models with a 1 per cent per annum compound change in carbon dioxide concentration, from the present through to 2100. Under this scenario, a doubling of pre-industrial equivalent carbon dioxide concentration occurs by about the year 2020, with a quadrupling by 2090. This is similar to the combined effect of all the gases in the IS92a emissions scenario. The future global-mean temperature change under this 1 per cent forcing scenario is about 0.3°C per decade, following a simulated temperature rise from 1860-1995 of about one degree C.

Ensembles

The model predictions of climate change could depend upon the choice of point on the control run at which the increasing greenhouse gas concentrations are introduced. For this reason, four identical model experiments, with the same historical changes and future changes in greenhouse gases, are initiated from four different points on the control run; this is known as an "ensemble" of predictions. The underlying climate change predicted by each of these model experiments is very similar, showing that the initial condition is not important to the long-term change. However, there are significant year-to-year and decade-to-decade differences due to natural variability, particularly at a regional level such as over the UK (see Figure 1). For this reason, results from the four members of the ensemble are sometimes averaged together. This has been done to produce the climate scenarios used in this Report.

Aerosols

Climate can also be affected by a number of other agents in addition to greenhouse gases; important amongst these are small particles (aerosols). These are suspended in the atmosphere and reflect back solar radiation, hence they have a cooling effect on climate. Although there are no measurements to show how these have changed over the past 150 years, there are estimates of how sulphur dioxide emissions have risen, and projections of emissions in the future, and these are used in a sulphur cycle model to calculate the accompanying rise in sulphate aerosols. When these are used as input to HadCM2, the global temperature rise to 2100 is reduced by about one third.

However, this is a very uncertain calculation due to a number of factors. Firstly, the IPCC emissions scenario on which it was based contains large rises in sulphur dioxide emissions over the next century; more recent estimates of these emissions see only a small rise over the next couple of decades followed by reductions to levels lower than today's by 2100. The inclusion of such a sulphur dioxide scenario would actually produce a temperature rise by 2100 relative to a model experiment that excluded the aerosol effect. Secondly, more recent sulphur cycle models generate a lower sulphate burden per tonne of sulphur dioxide emissions and the radiative effect of the sulphate particles in more sophisticated radiation models is smaller than previously calculated. In addition to the direct effect of sulphate aerosols, they can also cool climate by changing the reflectivity and longevity of clouds; these indirect effects are now realised as being as at least as important as the direct effect but were not included in HadCM2 simulations. Above all, the short lifetime of sulphate particles in the atmosphere means that they are to be seen as a temporary masking effect on the underlying warming trend due to greenhouse gases. For all these reasons, HadCM2 simulations of future climate change that include aerosols have not been used to develop scenarios in this Report.

Appendix 3: The IS92 and SRES98 Emissions Scenarios

The IS92 Emissions Scenarios

Six emissions scenarios (IS92a to f) were published in the 1992 Supplementary Report to the IPCC Assessment (Leggett et al., 1992[a]. These scenarios embodied a wide array of assumptions affecting how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted. The different worlds that the scenarios imply, in terms of economic, social and environmental conditions, vary widely and the resulting range of possible greenhouse gas futures spans almost an order of magnitude.

IS92a represents a middle-of-the-range scenario due to modest and largely offsetting changes in the underlying assumptions. Population rises to 11.3 billion by 2100 and economic growth averages 2.3 % per annum between 1990 and 2100, with a mix of conventional and renewable energy sources being used. The highest greenhouse gas emissions result from the IS92e scenario that combines, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and eventual hypothetical phase-out of nuclear power. At the other extreme, IS92c has a CO_2 emissions path that eventually falls below its 1990 starting level. It assumes that population first grows, then declines by the middle of next century, that economic growth is low, and that there are severe constraints on fossil fuel supply.

The SRES98 Emissions Scenarios

The plenary session of IPCC in 1996 charged Working Group III of the Panel to develop a Special Report on Emissions Scenarios (SRES), including a new set (i.e., replacing the IS92 scenarios) of scenarios for the emissions of greenhouse gases. The scenarios are all 'non-intervention scenarios', implying that no explicit additional climate policies are to be assumed. In early 1997, a writing team with broad representation from all regions and from industrial and environmental NGOs started the preparation of this report under the leadership of Dr. Nakicenovic of IIASA. The writing team has:

- performed an extensive review of the literature, pertinent to emissions of greenhouse gases and the associated driving forces
- developed an extensive scenario database
- developed four sets of qualitative storylines describing possible futures
- concluded a preliminary quantification of these storylines in terms of energy and land use emissions.

These four 'template scenarios' (A1, A2, B1, B2) are representative of the wide spectrum of scenarios found in the literature.

An important component of the terms of reference of SRES is a so-called 'open process', to stimulate the participation of a group of experts wider than the writing team, especially from different regions and societal sectors. Three main contributions are invited: (a) scenarios that have escaped the attention of the writing team, (b) new scenario quantifications based on the template scenarios, and (c) general suggestions to add to the work of the writing team to date. The open process is being implemented by CIESIN (The Center for International Earth Science Information Network, Columbia University) in the USA in close collaboration with the Technical Support Unit of Working Group III and the Energy Research Foundation in the Netherlands. The open process will end by December 31st 1998. Only on completion of the open process, and the subsequent revision of the SRES98 scenarios by the Task Group, will the new scenarios be formally adopted by the IPCC and be termed the IS99 scenarios. More information on the SRES scenarios, including preliminary quantification, can be found at the CIESIN web site (see Appendix 8).

The new set of reference scenarios is intended for use in future IPCC assessments and by the wider scientific and other communities working on impacts of future greenhouse gas emissions and on mitigation measures and policies. Scenarios can provide the emissions profiles as inputs to global climate models and simplified models of regional climate change. They can provide the reference information required for the assessment of impacts of climate change, such as the level of economic activity in different world regions, rates of technological change, or population growth. The same kind of information, in conjunction with emissions trajectories, can serve as benchmarks for the evaluation of alternative mitigation measures and policies.

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Appendix 4: The Observed British Isles Climate Datasets

The CRU 10 km British Isles Climatology

A number of attempts have been made to construct gridded climate surfaces for parts of the British Isles from scattered station observations. These have used both multiple regression and spatial interpolation techniques, but have almost always been confined to either a limited number of climate variables, a smaller domain than the whole of the British Isles, or have been based on short or non-standard records of climate. Partial thin-plate splines, a technique developed for climate applications by Mike Hutchinson, were used to construct the mean 1961-90 climatology used in this Report[a]. This technique included elevation as an independent predictor variable, in addition to the more usual latitude and longitude. The number of stations used to construct the climate surfaces was dependent on the climate variable in question. The number of stations ranged from eighty, in the case of wind speed, to 750 for precipitation. The precipitation data set contained almost 9,000 sites, but only 750 of these were used in the interpolation. The climatology used in this Report represents, to the best of our knowledge, the most contemporary, comprehensive and widely-available climate dataset for the British Isles presently in use. Maps and data files extracted from this climatology are provided on the CD-ROM.

The CRU 0.5° Global Climatology

The CRU05 Global Climate Dataset consists of a multi-variate 0.5° latitude by 0.5° longitude resolution mean monthly climatology for global land areas, excluding Antarctica, strictly constrained to the period 1961-90, together with monthly time series at the same resolution for the period 1901-95. The mean 1961-90 climatology comprises a suite of eleven surface variables: precipitation and wet-day frequency; mean, maximum and minimum temperature; vapour pressure and relative humidity; sunshine percent and cloud cover; frost frequency; and wind speed. The time series component comprises all variables except sunshine per cent, frost frequency and wind speed, variables that are still under development.

The mean climate surfaces have been constructed from a new dataset of station 1961-90 climatological normals, numbering between 19,800 (precipitation) and 3615 (windspeed). The station data were interpolated as a function of latitude, longitude and elevation using thin-plate splines. The accuracy of the interpolations are assessed using cross-validation and by comparison with other climatologies.

The anomaly time series were constructed using historic anomalies derived from the monthly data holdings of the Climatic Research Unit and the Global Historic Climatology Network. For the purposes of developing monthly gridded time series, the variables were classified as either primary or secondary. For the primary variables - PRE, TMP, TMX, TMN - sufficient data were available to enable interpolation directly from the station time series. In the case of secondary variables - CLD, VAP, REH, WET - the available station time series were sparsely sampled in space and time. These variables had to derived indirectly from gridded time series of primary variables. Station data that were available for secondary variables were used to develop relationships to the primary variables and to validate the derived gridded time series.

To calculate monthly time series, grids of monthly anomalies relative to 1961-90 were calculated for each variable and applied to their respective 1961-90 climatology. The anomaly approach was adopted because the network of station normals was much more comprehensive than the network of station time series. The spatial variability in mean climate was best captured by the denser network of station normals, while the more sparse network of primary variable time series captured as much temporal variability as possible. A paper describing this full dataset is under review for publication, but initial details can be found under the homepage of Mark New (http://www.cru.uea.ac.uk/~markn/). Selected fields and time series from this climatology can be viewed through the Data Visualisation pages of the IPCC Data Distribution Centre. Decade-mean and 30-year mean monthly fields can be downloaded from the Data Download pages. Access to the full year-by-year monthly dataset is achieved by lodging a request with the Climate Impacts LINK Project at the Climatic Research Unit (email: d.viner@uea.ac.uk, web site: http://www.cru.uea.ac.uk/link).

a E.M.Barrow, M.Hulme and T.Jiang, **A 1961-90 Baseline Climatology and Future Climate Change Scenarios for Great Britain and Europe. Part I: 1961-90 Great Britain Baseline Climatology,** a report accompanying the datasets prepared for the 'Landscape Dyanmics and Climate Change' TIGER IV Consortium, Norwich, Climatic Research Unit, 1993.

Appendix 5: The IPCC Data Distribution Centre

A Data Distribution Centre (DDC) has been established by the IPCC to facilitate the timely distribution of a consistent set of scenarios of changes in climate and related environmental and socio-economic factors for use in climate impacts assessments. The intention is that these new assessments can feed into the review process of the IPCC, in particular to the Third Assessment Report (TAR) due to be published in 2001. The initiative to establish a DDC grew out of a recommendation by the IPCC Task Group on Climate Scenarios for Impacts Assessments and the Centre is currently run by the Climatic Research Unit in the UK and the Deutsches Klimarechenzentrum in Germany. Regional mirror sites may be added in the future.

The purpose of the DDC is to set the stage for the rapid uptake of results from more recent climate change experiments by researchers in the impacts community and to improve the consistency of the scenarios adopted in different national and international assessments. The DDC, by distributing climate scenario and related information to climate change impacts researchers throughout the world, ensures that all researchers have the possibility of working with a consistent set of climate scenarios. This co-ordination allows climate change impacts research to be better integrated globally, thus enhancing the value of the IPCC Third Assessment Report.

The DDC provides four types of data or information. These are made available to impacts researchers through a variety of media, including the internet, CD-ROMs and tapes. There is a DDC helpline for user enquiries. The four types of information are:

- Observed Global Climate Datasets. These include a gridded terrestrial climatology of mean monthly data for 1961-90 on a 0.5° latitude/longitude grid, together with decadal anomalies from this mean for the period 1901-95.
- Socio-economic Scenario Information. The socio-economic scenario data supplied are taken from the assumptions behind both the IS92 emissions scenarios and the new emissions scenarios to emerge from the IPCC Special Report on Emissions Scenarios (SRES).
- Results from GCM Experiments. These monthly surface climate data have been extracted from recent transient, warm-start simulations which include both greenhouse gas only and greenhouse gas and sulphate aerosol forcings. Consistent scenarios of global sea-level change and carbon dioxide concentrations are provided.
- Guidance Material. This document provides descriptions of the GCM experiments, discussion of scenario uncertainties, guidance on their application in impacts studies, and reporting guidelines for research results.

The DDC web site has been designed to allow the user quick and easy access to the full range of scenario information. The site can be accessed at http://ipcc-ddc.cru.uea.ac.uk/. The DDC web site has four main functions:

- User Registration and Orders for the CD-ROM. The DDC CD-ROM is provided free of charge.
- User Support. This provides information about the datasets available from the DDC and a list of Frequently Asked Questions (FAQs) about the use and application of scenario data.
- Data Visualisation. Web-based software allows viewing of the various climate datasets in map and graphical form.
- Data Download. The web site allows users to download (ASCII or binary) data files from the DDC. These datasets include global observed climate baseline data, aggregate climate change fields from the GCMs, and socio-economic scenario data.

Appendix 6: Quantification of Global Climate Changes

	2020s			2050s			2080s		
	ΔT	ΔSL	CO_2	ΔT	ΔSL	CO_2	ΔT	ΔSL	CO_2
	deg C	*cm*	*ppmv*	*deg C*	*cm*	*ppmv*	*deg C*	*cm*	*ppmv*
IPCC 1995									
IS92*a*	0.96	20	434	1.68	38	528	2.37	58	637
IS92*b*	0.94	20	431	1.64	38	519	2.31	57	620
IS92*c*	0.84	19	413	1.27	34	452	1.50	47	468
IS92*d*	0.84	19	415	1.33	34	467	1.71	49	515
IS92*e*	1.04	21	452	1.96	41	591	2.96	65	805
IS92*f*	1.02	21	446	1.86	40	563	2.74	62	718
CCIRG96	0.92	19	433	1.63	37	525	N/*a*	N/*a*	N/*a*
Kyoto Scenarios									
K1	0.93	20	428	1.61	37	511	2.25	56	606
K2	0.93	20	426	1.57	37	499	2.15	55	579
K3	0.93	20	426	1.49	36	479	1.87	52	503
UKCIP98									
Low	0.57	7	415	0.89	12	467	1.13	18	515
Medium low	0.98	8	398	1.52	18	443	1.94	29	498
Medium high	1.24	12	447	2.11	25	554	3.11	41	697
High	1.38	38	434	2.44	67	528	3.47	99	637
Aerosol Scenarios									
HadCM2 GS*a*	0.94	N/*a*	447	1.58	N/*a*	535	2.58	N/*a*	687
HadCM2 GS*d*	0.76	N/*a*	398	1.41	N/*a*	443	1.86	N/*a*	498

Table A.1: Global climate change estimates for three future periods and for various scenarios. Results for the IS92 scenarios, for the CCIRG96 scenario, for various interpretations of the Kyoto Protocol and for the sulphate aerosol runs from HadCM2 are shown for comparison with the UKCIP98 scenarios. All changes are with respect to 1961-90. The IPCC95 and Kyoto scenarios are calculated using the MAGICC climate model (IPCC Second Assessment Report version, courtesy of Tom Wigley and Sarah Raper), with a climate sensitivity of 2.5°C and no aerosol effects. The Kyoto scenarios are explained in the main text and shown in Figure 11.

Appendix 7: Technical Considerations in the Application of Climate Change Scenarios

In this Appendix we identify a number of specific technical issues to be alert to when applying or interpreting some of the climate change scenario data presented in this Report or supplied on the accompanying CD-ROM.

The Uses of Scenarios

Climate change scenarios should be used to inform a sensitivity analysis of climate change impact rather than be treated as definitive predictions of the future. We have deliberately created four different climate futures in the UKCIP98 scenarios to indicate that climate prediction is an uncertain activity. These four scenarios span a fair part of the likely future climate range, but do not fully encompass it. For example, we have based our results from only one global climate model (HadCM2) and we have not considered an emissions growth rate higher than IS92a (or about 1 % per annum growth in overall greenhouse gas concentrations). We encourage users of the UKCIP98 scenarios to use more than one of the four scenarios in their impact assessment.

Appreciating Natural Climate Variability

Future climate in the UK will be different from that of 1961-90, even without any human influence on the climate system. We have provided estimates in Chapter 7 of how much UK climate may vary naturally. We believe it is important for impact assessors to appreciate this level of natural climate variability, and the impact it may have, before progressing to consider the changes caused by the enhanced greenhouse effect. For example, we have shown that summer rainfall in southern Britain varies naturally on 30-year time-scales by up to 10 per cent or more. If the period around the 2020s is, for example, 10 per cent drier in summer than 1961-90 what will this mean for water management in the UK? Whatever it signifies will not necessarily be a result of human-induced climate change.

Grid-box Versus Station Values

Throughout this report we have usually presented information at the scale of the grid-boxes in the HadCM2 model. These values represent changes in climate over very large areas. Particularly for extreme events on daily time-scales (e.g. intense rainfall, storms, heatwaves), global climate models therefore generate statistics that are quite different from those measured at individual weather stations. The analyses of extremes contained in the UKCIP98 scenarios should be treated cautiously and merely as illustrative. The GCM grid-box changes should not be blindly applied to observed frequencies of such events obtained from individual station data. What is needed in such cases is some form of intelligent downscaling (see Chapter 6).

The Dangers of 'Unintelligent' Downscaling

Chapter 6 discussed different downscaling methods and explained how the 10 km climate scenario data files on the CD-ROM were generated. The 'unintelligent' downscaling method used here was to interpolate values from a 2.5° latitude by 3.75° longitude GCM grid onto a 10 km grid for the UK and then add them to the baseline 10 km climatology. This simple approach adds no real geographical detail to the climate change derived from the GCM. It cannot, for example, account for the climate change at the top of Ben Nevis being different from that experienced at Fort William at the bottom of the mountain.
In particular, this approach introduces inconsistencies around the coastline of the UK; the land-ocean mask of HadCM2 is quite different from the land-ocean mask of the 10 km climatology, so in some cases oceanic climate changes from the GCM are applied to 10 km land cells. Only more sophisticated downscaling methods would avoid this problem.

Using Scaled GCM Results

The patterns for the UKCIP **Low** and **High** scenarios are derived, respectively, from the ensemble-mean patterns of the **Medium-low** and **Medium-high** scenarios. While the patterns of these scenario pairs are the same, the magnitudes are different and result from the relative difference in global warming between the different scenarios. Thus the magnitude of the climate change patterns in the **Low** scenario is about 42 % smaller than in the **Medium-low,** and those in the **High** scenario about 11 % higher than in the **Medium-high** scenario (cf. Table 4). Scaling GCM results in this way is a convenient solution to the scarcity of GCM experiments that have sampled the full range of climate prediction uncertainties - those caused by different emissions scenarios and those caused by different climate sensitivities (most global climate models exhibit a climate sensitivity between 2.5°C and 3.5°C rather than sample the full IPCC range of 1.5°C to 4.5°C). Scaled scenarios rely on a number of assumptions: that climate change is basically linear, that patterns of climate change are independent of the history of greenhouse gas forcing, and that GCMs adequately define the climate change signal. In the absence of a larger sample of GCM experiments to draw upon, scaled scenarios will continue to be used in impacts assessments.

Appendix 8: Further Sources of Information on Climate Data and Scenarios

- **The Climate Impacts LINK Project: http://www.cru.uea.ac.uk/link/**
  Dr David Viner (d.viner@uea.ac.uk)
  Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK
  Tel: 01603 592089; Fax: 01603 507784

- **The Hadley Centre for Climate Prediction and Research: http://www.met-office.gov.uk/sec5/sec5pg1.html**
  Dr Geoff Jenkins (gjjenkins@meto.gov.uk)
  Hadley Centre, London Road, Met. Office, Bracknell RG12 2SY
  Tel: 01344 856653 ; Fax: 01344 854898

- **The UK Climate Impacts Programme: http://www.ecu.ox.ac.uk/ukcip.html**
  Dr Merylyn Mackenzie-Hedger (merylyn.hedger@ecu.ox.ac.uk)
  Programme Co-ordinator, UK Climate Impacts Programme, Environmental Change Unit, 1a Mansfield Rd, Oxford OX1 3TB, UK
  Tel: 01865 281192; Fax: 01865 281188

- **The British Atmospheric Data Centre (BADC): http://tornado.badc.rl.ac.uk/**
  Dr Lesley Gray (lesley.gray@rl.ac.uk)
  Middle Atmosphere Science Group, Space Science Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
  Tel: 01235 446745; Fax: 01235 445848

- **The Inter-governmental Panel on Climate Change (IPCC): http://www.ipcc.ch/**
  IPCC Secretariat
  WMO Building, 41 Av. Giuseppe-Motta, Case postale No. 2300, 1211 Geneva 2, Switzerland
  Fax: +41 22 733 1270

- **The IPCC Data Distribution Centre (DDC): http://ipcc-ddc.cru.uea.ac.uk/** (see Appendix 5)
  Dr Mike Hulme (m.hulme@uea.ac.uk)
  Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK
  Tel: 01603 593162; Fax: 01603 507784

- **The IPCC Special Report on Emissions Scenarios (SRES): http://sres.ciesin.org/index.html** (see Appendix 3)
  CIESIN User Services
  P.O. Box 1000, 61 Route 9W, Palisades, NY 10964, USA
  Telephone: +1-914-365-8920; Fax: +1-914-365-8922.

- **The LARS Weather Generator: http://www.lars.bbsrc.ac.uk/model/larswg.html**
  Dr Mikhail Semenov (mikhail.semenov@bbsrc.ac.uk)
  IACR Long Ashton Research Station, Department of Agricultural Sciences, University of Bristol
  Long Ashton, Bristol BS41 9AF, UK
  Tel: 01275 392181; Fax: 01275 394007

Appendix 9: UKCIP98 Climate Scenario CD-ROM Contents

(see inside back cover for ordering details)

A. Electronic version of the CD-ROM User Licence

B. The full UKCIP Scenario Report in PDF Format

C. Additional Set of Maps in PDF Format

Observed mean 1961-90 seasonal and annual fields, with 1901-1995 time series, for:

- Mean temperature, diurnal temperature range, precipitation, number of wet days, cloud cover, vapour pressure.

Observed mean 1961-90 seasonal and annual fields for:

- Number of frost days, global radiation, mean wind speed, sunshine, relative humidity, interannual and inter-daily temperature variability, interannual and inter-daily precipitation variability, and mean maximum daily wind speed.

Mean seasonal and annual GCM change fields for the 2020s, 2050s, and 2080s for the four UKCIP98 scenarios for:

- Mean temperature, diurnal temperature range, precipitation, cloud cover, vapour pressure, mean wind speed, and potential evapotranspiration.

D. Observed 1961-90 and UKCIP98 Scenario Climate Data Files in ASCII Format

The observed files contain mean monthly, seasonal and annual data at a 10 km resolution for Great Britain (2785 pixels) and Ireland (990 pixels). The 10 km grids for these two domains are shown in Figures A.1 and A.2. The following variables are supplied:

- Mean, maximum and minimum temperature, diurnal temperature range, number of frost days, precipitation, number of wet days, cloud cover, global radiation, sunshine, vapour pressure, mean wind speed, potential evapotranspiration, interannual and inter-daily temperature variability, interannual and inter-daily precipitation variability, and mean maximum daily wind speed.

The scenario files contain mean monthly, seasonal and annual data at a 10 km resolution for Great Britain and Ireland for the periods 2010-2039 (2020s), 2040-2069 (2050s) and 2070-2099 (2080s) for all four UKCIP98 scenarios and for the following variables:

- Mean, maximum and minimum temperature, diurnal temperature range, precipitation, cloud cover, vapour pressure, mean wind speed, potential evapotranspiration, interannual temperature variability, and interannual precipitation variability.

Also supplied are the GCM mean change fields at HadCM2 resolution (49 grid cells) for the British Isles, for all four UKCIP98 scenarios, for the three 30-year periods (with respect to 1961-90) and for the following variables:

- Mean, maximum and minimum temperature, diurnal temperature range, precipitation, cloud cover, vapour pressure, relative humidity, mean wind speed, potential evapotranspiration, interannual temperature variability, and interannual precipitation variability.

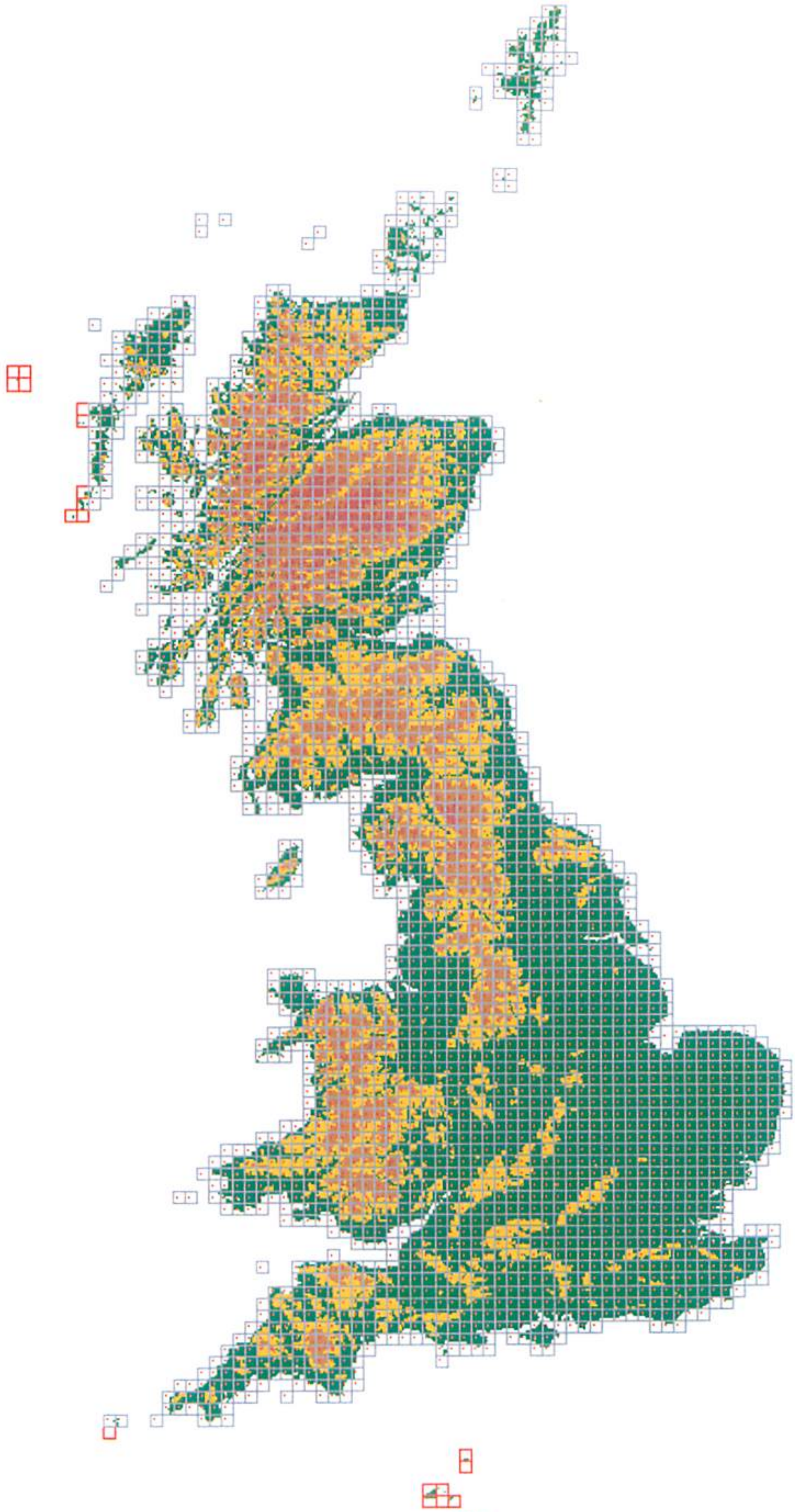

Figure A.1: *The 10 km land grid for Great Britain.*

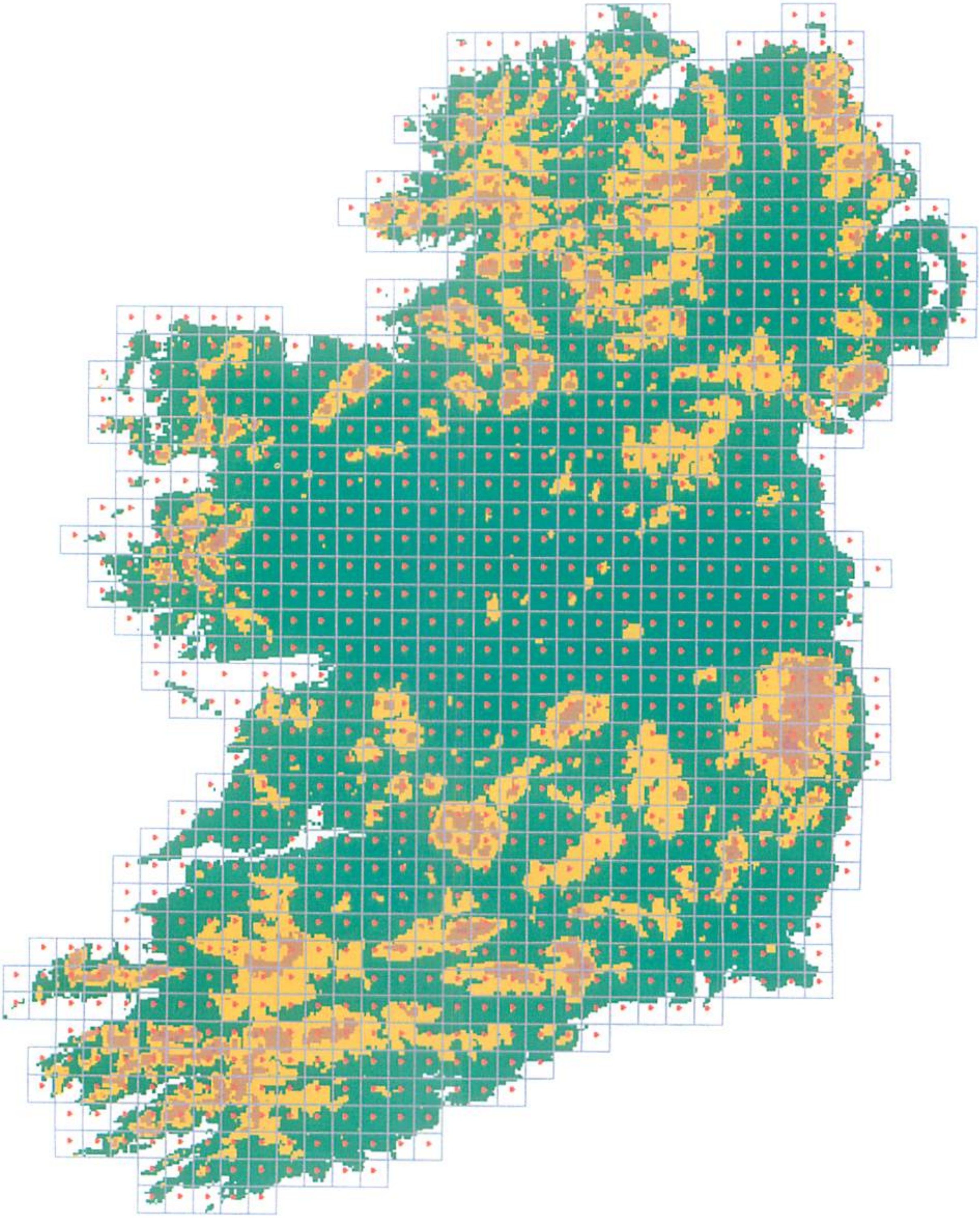

Figure A.2: The 10 km land grid for Ireland.

Appendix 10: UKCIP98 Climate Scenario CD-ROM User Licence

This agreement is between the Climate Impacts LINK Project (Climatic Research Unit, University of East Anglia) and The Met. Office/Hadley Centre (the Authorities) under Department of the Environment, Transport and the Regions contract EPG 1/1/68 and:

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This form should be photocopied and returned to:

Climate Impacts LINK Project
Climatic Research Unit
University of East Anglia
Norwich NR4 7TJ United Kingdom

Fax: 01603 507784

Obtaining the UKCIP98 Climate Scenario CD-ROM

Further copies of this report, or of the 16 page summary version, and the CD-ROM containing the scenario data can be obtained from one of the following two places. These products are free, although users of the CD-ROM will need to complete a Registration Form and abide by the terms and conditions of use.

Data Manager
UK Climate Impacts Programme
Environmental Change Unit
1a Mansfield Road, Oxford OX1 3TB
Tel: 01865 281192 Fax: 01865 281188
Email: ukcip@ecu.ox.ac.uk

Climate Impacts LINK Project
Climatic Research Unit
University of East Anglia
Norwich NR4 7TJ
Tel: 01603 592089 Fax: 01603 507784
Email: d.viner@uea.ac.uk

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